



HAL
open science

Colwellia and sulfur-oxidizing bacteria: An unusual dual symbiosis in a Terua mussel (Mytilidae: Bathymodiolinae) from whale falls in the Antilles arc

Sébastien Duperron, Olivier Gros

► **To cite this version:**

Sébastien Duperron, Olivier Gros. Colwellia and sulfur-oxidizing bacteria: An unusual dual symbiosis in a Terua mussel (Mytilidae: Bathymodiolinae) from whale falls in the Antilles arc. Deep Sea Research Part I: Oceanographic Research Papers, 2016, 115, pp.112-122. 10.1016/j.dsr.2016.05.012 . hal-01336943

HAL Id: hal-01336943

<https://hal.sorbonne-universite.fr/hal-01336943>

Submitted on 24 Jun 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

***Colwellia* and sulfur-oxidizing bacteria: an unusual dual symbiosis in a *Terua* mussel
(Mytilidae: Bathymodiolinae) from whale falls in the Antilles arc**

Sébastien Duperron^{1,2*} and Olivier Gros^{3,4}

5 ¹ Sorbonne Universités, UPMC Université Paris 06, UMR7208 Laboratoire biologie des organismes
et écosystèmes aquatiques (UPMC CNRS MNHN IRD CAEN), 7 quai St Bernard, 75005 Paris,
France

² Institut Universitaire de France, Paris, France

³ Institut de Biologie Paris-Seine, UMR 7138 - Evolution Paris-Seine, Equipe Biologie de la
10 Mangrove. Université des Antilles, UFR des Sciences Exactes et Naturelles, Département de
Biologie, BP 592. 97159 Pointe-à-Pitre cedex, Guadeloupe, France.

⁴ C₃MAG, UFR des Sciences Exactes et Naturelles, Université des Antilles, BP 592. 97159 Pointe-à-
Pitre, Guadeloupe (French West Indies).

15 * Corresponding author

E-mail: sebastien.duperron@upmc.fr

Running title: Dual symbiosis in mussels colonizing sunken bones in Caribbean

Keywords: Caribbean sea, symbiosis, whale falls, sulfur-oxidizing bacteria, *Colwellia*, *Terua*.

20

Abstract

Seven individuals of a single morphotype of mussels (Bivalvia: Mytilidae) were found attached to a naturally sunken whale intervertebral disk collected in Guadeloupe (Caribbean) at 800 m depth. These specimens resemble small *Idas* mussels which are found worldwide at cold seeps and hydrothermal vents, and typically harbour ectosymbiotic bacteria on their gills upon which they depend for nutrition. Based on multi-locus gene sequencing, these specimens appear to belong to a new species closely related to two species now included within the genus *Terua*. Unexpectedly, its closest relatives are found in the Pacific, questioning how this species has reached the Antilles arc. Based on marker gene sequence analysis, electron and fluorescence microscopy, *Terua* n. sp. harbours two distinct and abundant extracellular bacterial symbionts located between microvilli at the apical surface of host gill epithelial cells. One is a sulfur-oxidizing bacterium similar to the symbionts previously identified in several deep-sea mussels, while the other is related to *Colwellia* species, a group of cold-adapted heterotrophic bacteria able to degrade organic compounds. This study provides the first evidence for the existence of a dual symbiosis in mussels from whale fall ecosystems in the Caribbean. The evolutionary history of *Terua* n. sp. and potential role of its *Colwellia* symbionts are discussed.

Introduction

Large mussels associated with deep-sea hydrothermal vents and cold seeps have been studied since their discovery in the late 1970s. Their abundance at many sites and their nutritional reliance on dense populations of gill-associated bacterial symbionts which use reduced sulfur or methane to produce their organic matter attracted interest from many researchers. They form the clade Bathymodiolinae, named after the genus *Bathymodiolus* (Kenk & Wilson, 1985) in which most large mussels are included. Many papers have investigated how these symbiotic bivalves could thrive in *a priori* inhospitable habitats and how they had evolved (Dubilier *et al.*, 2008; Duperron, 2010). Over the last decade smaller mussels, some described in the 19th century and overlooked since then, were shown to also belong to the Bathymodiolinae clade (Lorion *et al.* 2010, 2013; Thubaut *et al.* 2013). They live in reducing habitats including vents and seeps, but also on sunken carcasses of large animals and on wood falls, the decaying of which releases reduced compounds including sulfide and methane. The classification of small mussels is challenging because genus names do not overlap with gene phylogeny-based clades, but small species are of prime importance if we are to understand the evolution of deep-sea symbiont-bearing mussels. Indeed, large mussels cluster within a limited number of terminal clades, appearing as

55 derived specialized forms, while the rest of the Bathymodiolinae phylogeny consists of various
groups of small mussels. Biologically-speaking, apart from their small size, they share important
features with large mussels, including the presence of bacterial symbionts in their gills (Deming *et*
al. 1997; Gros and Gaill 2007; Duperron *et al.* 2008b; Southward 2008). However their symbioses
seem to be more diverse and flexible. Large mussels usually have one to four types of bacteria
60 located inside their gill epithelial cells. Small mussels on the other hand can display intra- or
extracellular bacteria, a greater diversity of symbionts with up to 6 distinct types co-existing in the
gills of *Idas modiolaeformis*, not restricted to sulfur- and methane-oxidizers, and the composition of
bacterial communities can vary between sites for a given species (Duperron *et al.* 2008a; Laming *et*
al. 2015b). Unfortunately, because of the patchy and unpredictable occurrence of their habitats,
65 small mussels are often collected by chance in very limited numbers. Nevertheless their study yields
important information for our understanding of the diversity, biogeography and evolution of the
fauna colonizing deep-sea reducing habitats.

Seven species of Bathymodiolinae mussels are currently reported from the Gulf of Mexico
and Antilles arc, all from cold seep habitats. Four are large *Bathymodiolus* (*B. keckerae*, *B.*
70 *boomerang*, *B. brooksi*, *B. childressi* and a yet unnamed species), and two are smaller species,
namely *Tamu fisheri* usually collected from 540-700 m depth associated with vestimentiferan
tubeworm bushes, and *Idas macdonaldi* from 650 m depth (Gustafson *et al.* 1998; Faure *et al.*,
2015). Dell (1987) also mentions *Idas dalli* E.A. Smith 1885 sampled from the Culebra Island
(Porto Rico, West Indies) during the Challenger expedition, but little data is available. Seven mussel
75 individuals representing a single morphotype were recently found attached to an inter-vertebral disk
of a naturally sunken whale collected near Guadeloupe (Caribbean) at 800 m depth. In this study we
test whether these represent a new species, or one of the 7 previously documented from the region,
using multiple marker gene sequencing and phylogeny. We also characterize associated bacterial
symbionts using electron microscopy, marker gene sequencing and fluorescence *in situ*
80 hybridization (FISH). Results are discussed with a special emphasis on mussel biogeography, and
on the potential role of the identified symbionts. This study is the first investigation of bone-
associated symbiotic mussels from the Antilles arc.

Materials and methods

85

Sample collection and preparation

One inter-vertebral disk from a whale carcass was collected using a beam-trawl 780-820 m
depth during the karubenthos2 cruise (June 2015, chief scientist: P. Bouchet) around Guadeloupe in

the Caribbean [16°23'N, 60°46'W]. Mussel individuals up to 2 cm in length were found attached to
90 the surface of a spinal disk obtained from a unique naturally submerged whale carcass. Mussel
samples were processed onboard within 1 hour after collection.

Six mussel individuals were stored in 100% ethanol for molecular investigation of bacterial
diversity (see below) after severing adductor muscles. One individual was prepared for electron
microscopy. The two adductor muscles were severed in order to open the bivalve, then the whole
95 animal was pre-fixed in 2.5% glutaraldehyde / 0.1M cacodylate buffer (pH 7.2) adjusted to 900
mOsM with NaCl and CaCl₂ and stored at 4°C. Two weeks later, after returning to the laboratory,
the gills were dissected into three parts. Scanning Electron Microscope (SEM) and Transmission
Electron Microscope (TEM) were performed to detect possible symbiosis. Samples for SEM
observations were rinsed twice in the same buffer then dehydrated in graded concentrations of
100 acetone, critical point dried in CO₂ and sputter-coated with gold before observation with a FEI
Quanta 250 at 20kV. For TEM observations, samples were rinsed in the same buffer, fixed for 45
minutes at room temperature in 1% osmium tetroxide in the same buffer with a final osmolarity
adjusted to 1000mOsm, then rinsed in distilled water and post-fixed with 2% aqueous uranyl acetate
for one more hour at RT before embedding in epon-araldite resin and observation in a FEI Quanta
105 250 at 15kV under the STEM mode.

Energy-dispersive X-ray spectroscopy (EDXs) analysis

In order to detect elemental compounds from the gill (such as sulfur), the gill fragment
stored in the fixative solution was observed using an Environmental Scanning Electron Microscope
110 (FEI Quanta 250) operating at 10 kV under an environmental pressure of 7 torr at 8°C. EDX spectra
were obtained using a X-max 50 mm² Oxford SDD detector. Gills were rinsed briefly in distilled
water (to remove salts) and observed without prior dehydration.

Gene sequence analysis

115 DNA was extracted from the gill tissue from two specimens according to the protocol previously
described (Duperron *et al.* 2005). Fragments of host genes encoding H3 histone, 28S rRNA,
mitochondrial cytochrome oxidase I (mtCOI) and mitochondrial 16S rRNA (mt16S), and fragments
of bacterial genes encoding 16S rRNA and APS reductase were amplified by PCR. Products were
cloned (products from 3 parallel PCR were pooled prior to cloning for bacterial 16S rRNA) using
120 the PCR® 2.1-TOPO TA cloning kit (Invitrogen, CA), and inserts from selected clones were
sequenced by GATC Biotech (Germany). PCR primers, cycling conditions and number of analysed
clones are summarized in table 1. Sequences were deposited under GENBANK accession numbers

KU747145-KU747153.

For each gene, representative sequences, their best hits according to BLAST (Altschul *et al.* 1990) and selected available sequences were aligned using ClustalX. Alignments were manually curated and phylogenetic reconstructions were performed using Mega v.6 using a Maximum Likelihood (ML) approach under a General Time Reversible (GTR) model. To account for different substitution rates among sites, gamma-distributed rates with 5 categories and invariants were included. For host genes, a multi-gene phylogeny was produced using concatenated sequences of mtCOI, mt16S and H3.

Fluorescence *in situ* hybridization (FISH)

Specimens were embedded in Steedman's wax or LR-White according to described protocols, and sectioned using a microtome (Thermo). FISH was performed using standard probes Eub-338 and Non-338 as positive and negative controls, respectively. Probe Bthio-193 displayed perfect match with the 16S rRNA-encoding sequence related to sulfur-oxidizing (SOX) bacteria and was used to test for its presence in the tissues (5'-CGAAGATCCTCCACTTTA-3' (Duperron *et al.* 2007)). Probe Alt1413 (5'-TTTGCATCCCCTCCCAT-3') showed no mismatch to the other, *Colwellia*-related abundant sequence in clone libraries and was used to test for the presence of this potential second bacterium (Eilers *et al.* 2000). It was designed to target the genus *Alteromonas* but also matches one third of available *Colwellia* sequences according to the ProbeMatch function of Ribosomal Database Project (Cole *et al.* 2009).

Hybridizations were performed according to Duperron *et al.* (2005) using buffers containing 30 and 40% formamide, and probes were labelled with Cy-3 or Cy-5. Slides were counterstained with DAPI, and observed under an Olympus BX61 epifluorescence microscope (Olympus, Japan).

Results

Host features

The 7 small mytilids (shell length between 9 and 12 mm long) displayed identical shell features, including a pink whole prodissoconch $445 \pm 13 \mu\text{m}$ in length (Figs. 1A, 2A-D) and an adult dissoconch appearing smooth under a binocular microscope. According to SEM views, prodissoconch I was small ($\sim 92 \pm 11 \mu\text{m}$) and the prodissoconch II measured $445 \pm 13 \mu\text{m}$ with several concentric growth lines (maximum length between two adjacent lines: $\sim 9 \mu\text{m}$). The visceral mass of two individuals (shell lengths of 10 and 12 mm) was filled with oocytes (not shown) indicating that they were adults, 6 fold above the size at maturity reported for the deep sea *Idas*

modiolaeformis (Laming *et al.* 2014). Mean oocyte diameter was 63 ± 5.7 μm (not shown).

Molecular identification of mussels

160 The two specimens from which host genes were sequenced displayed identical sequences for all 4 genes based on 6 to 12 clones (table 1). The sequence encoding 28S rRNA displayed only 1 out of 1002 base difference with sequences from *Adipicola pacifica* and ESU T, and above 99% identity with many sequences from various mussels. Due to this, 28S rRNA was not included in the concatenated analysis. Nucleotide sequences encoding mt16S, mtCOI and H3 all displayed ESU T
165 as their best hit with 97%, 89% and 100% sequence similarity, respectively. *Adipicola pacifica* usually came second with 93%, 84% and 99%, respectively. Phylogenetic reconstructions obtained for each gene placed ESU T, collected from bones at depths between 800 and 1060 m near the Vanuatu (Lorion *et al.* 2013), as a sister group to the mussels from this study with high bootstrap values (above 95%, not shown). The tree based on concatenate gene sequences confirmed that our
170 specimens were closely related to ESU sp. T, and that this group clustered with *Adipicola pacifica*, both nodes being supported by bootstrap values above 98% (Fig. 3).

Ultrastructural analysis of gill tissue

The overall structure of gill filaments in all specimens was comparable to that described previously
175 in other mussel morphotypes (Gros and Gaill 2007; Duperron *et al.* 2008b). According to SEM views, the creamy colored gills, which cover the visceral mass, are organized in consecutive gill filaments (Figs. 1B, 1D). The surface of the gills contains a dense covering of cilia that could carry food along a food groove (Figs. 1D-E) to the mouth region. The presence of such groove could suggest a mixotrophic feeding mode in this species. The ciliated zone is similar to that described in
180 other mytilid species with typical frontal, latero-frontal, and lateral ciliated cells (Fig. 4A). In the ciliated zone, the core of each filament is occupied by a collagen axis which encloses few fibroblasts, whereas, in the lateral zone, it is occupied by connective tissue and a blood lacuna (Figs. 4B-C). The intermediary zone is short as the first cell in contact with the ciliated zone contained bacteria on its surface for all the samples studied (Figs. 1F, 4C). The ciliated zone always appeared
185 devoid of bacteria.

A few gill filaments were analyzed in EDXs using an environmental SEM (Fig. 1B) searching for elemental compounds. The analysis showed that sulfur was one of the main elements detected from the gills where it was much more abundant than in mantle or foot (Fig. 1C and D), suggesting the putative presence of sulfur-oxidizing bacterial symbionts. Furthermore,
190 ultrastructural analyses of thin sections of the specimens observed by TEM confirmed that bacteria

were associated with the gill tissue and were mostly extracellular (Figs. 4B-C, 5C). Moreover, bacteria with a similar morphotype compared to the extracellular ones could be present within vacuoles (Figs. 4C, 5A, 5C). Gill epithelial cells displayed a basal nucleus (Figs. 4C, 5B), few lysosome-like structures (Figs. 5A, C) and numerous bacteria inside vacuoles (Figs. 4B-C, 5A) or
195 between the microvilli in their apical pole (Fig. 4C). The lateral zone of each filament consisted of a single cell type bearing the bacterial symbionts (Figs. 4 & 5). No intercalary cells and/or mucocytes could be detected in the samples analyzed.

Individually, the bacteria were small and rod shaped (1 μ m length, 0.3 μ m thick) with a cell wall typical of gram-negative bacteria (Figs. 4C, 5C). No stacked intracellular membranes typical of
200 methanotrophic symbionts were seen. Differences in the shape of individual bacteria are due to section orientation. However, two morphotypes could be distinguished from the gill sections. The first one was characterized by a ribosome-rich cytoplasm appearing as a black area, localized at the periphery of the cell while the center of the cell containing the DNA was clearer (Figs. 4C, 5A-C). This morphology is unusual compared to previously described sulfur-oxidizing bacterial symbionts
205 of bivalves. The second morphotype was characterized by a clearer cytoplasm (Figs. 4C, 5A-C). Both morphotypes seem to be equally (and randomly) distributed through the lateral zone of each gill filament. The first bacteriocytes contained extracellular, but no envacuolated bacteria, as shown by SEM (Fig. 1E) or TEM (Fig. 5B) views.

210 **Molecular identification of associated bacteria**

Two 16S rRNA-encoding gene sequences dominated clone libraries in both specimens investigated. The first phylotype displayed 10 out of 1501 base differences with *Colwellia* sp. ZS4-15 (FJ889666) cultured from Antarctic intertidal sediment (Yu *et al.* 2010), and above 99% sequence identity with various *Colwellia* including *C. psychroerythraea* 34H of which the full genome is
215 available (CP000083 (Methe *et al.* 2005)) and *C. rossensis* from pack ice (AY167311 (Brinkmeyer *et al.* 2003)). The second phylotype displayed 99% identical positions with various sequences recovered from sulfur-oxidizing symbionts associated with deep-sea mussels, differing from clone M1.2 from *Idas modiolaeformis* by 11 out of 1492 aligned positions (Duperron *et al.* 2008a). The phylogenetic reconstruction confirmed these affiliations (Fig. 6). The *Colwellia*- and SOX-related
220 phlotypes represented respectively 62.9 and 35.7% of clone sequences in specimen 1 (140 clones), and 41.2 and 58.0% in specimen 2 (131 clones). The three remaining clones (KU747151-3) corresponded to three distinct Epsilonproteobacteria related to various deep-sea bacteria. Several distinct sequences were obtained in clone libraries of the APS reductase-encoding gene. The most abundant, representing 13 of the 21 clones, was 93% and 98% (nucleotide and amino acids,

225 respectively) similar to sequences previously obtained from mussel-associated SOX symbionts, suggesting that it could belong to the SOX-related bacterium identified herein.

FISH-based identification of potential symbionts

230 Hybridizations using the probe Eub-338 confirmed the presence of dense bacterial populations associated with the lateral zone of gill filaments in all 3 specimens investigated. Probe Bthio-193 targeting SOX symbionts labelled only a fraction of the bacteria labelled with the general probe Eub-338 (Figs. 7A-B). SOX signals could usually be seen spanning a number of neighbouring bacteriocytes, while large areas of the lateral zone were devoid of such signals. Probe Alt1413 targeting the *Colwellia*-related phylotype hybridized with those bacteria that were not
235 labelled by Bthio-193 (Figs. 7C-D). Due to inappropriate fixation, FISH signals were not as sharp as could be, yet signals from probes Alt1413 and Bthio-193 did not seem to overlap, suggesting they succeeded in distinguishing the two main phylotypes identified in clone libraries.

Discussion

240

Unexpected occurrence of *Terua* n. sp. in the Antilles arc

According to various authors, the lack of specific shell features makes the latter poor predictors of species relatedness in small deep-sea mussels (Won *et al.*, 2008; Lorion *et al.* 2010). Marker gene sequence analysis has thus proven to be the most useful tool to properly assign species. Sequence-
245 based identification has revealed that most morphology-based genera within the Bathymodiolinae were not monophyletic. Genus names are thus of little help when describing mussel evolutionary relationships (Thubaut *et al.* 2013). Specimens from the present study clustered between *Adipicola pacifica* and ESU T. Their mtCOI nucleotide sequences differed by 16.4 and 11.4% from those of *A. pacifica* and ESU T, respectively, suggesting that they belong to a distinct, yet-to-be described
250 species. Thubaut and co-workers recently suggested that *A. pacifica* and ESU T should be classified within the genus *Terua* initially described by Dall and his colleagues in 1938 (Thubaut *et al.* 2013). Following their recommendation we refer to our specimens as *Terua* n. sp. Guadeloupe in the following sections. Small Bathymodiolinae occur in the North West Atlantic and Gulf of Mexico, including *Idas macdonaldi* (sister species to *I. modiolaeformis* in figure 3) and *Tamu fisheri*, but
255 they are not closely related to *Terua* n. sp. The closest relatives of *Terua* n. sp. are reported from the Pacific Ocean and are not related to any species recorded from the Antilles arc. Based on the 3 fossil-based calibrations used by Lorion *et al.* (2013) and using the RelTime method implemented in MEGA 6, *Terua* n. sp. Guadeloupe diverged from ESU T around 6.2 MYA. This is consistent

with the closure of the Isthmus of Panama. A date around 8-12 MYA is often used as a time
260 calibration in biogeography studies (Plouviez *et al.* 2013), however several studies question these
dates and suggest final closure of the seaway later, possibly as late as 3 MYA (Bartoli *et al.* 2005).
The divergence time estimated here suggests that colonization of the Gulf of Mexico by ancestors
of *Terua* n. sp. could have happened before the seaway closed.

The shell provides another type of information. Here, the prodissoconch I (PI) measured $92 \pm 11 \mu\text{m}$,
265 and the prodissoconch II (PII) measured $445 \mu\text{m} \pm 13 \mu\text{m}$, within the range of values published for
several other small Bathymodiolinae including *Idas modiolaeformis*, *I. argenteus*, *I. iwaotakii* or *I.*
simpsoni (74 to 96 μm for PI, ad 379 to 544 for PII, (Laming *et al.* 2015a)). Based on these values,
it can be assumed that *Terua* n. sp. displays dispersal features similar to those reported in other
clades within the Bathymodiolinae. The relatively small size of the oocytes (indeed with a low
270 vitelline content) observed in 2 individuals, as well as the small PI size both confirm planktotrophic
development in this new species of *Terua*. Similar oocyte diameter ($41.5 \pm 7.5 \mu\text{m}$) was described in
the small mytilid *Idas modioliformis* which displays a planktotrophic development (Gaudron *et al.*,
2012). Based on much larger PII compared to PI sizes, these previous studies also inferred that
larval life prior to settlement could potentially last for several months at low environmental
275 temperatures.

An unusual type of dual symbiosis

According to clone libraries and *in situ* hybridizations on gill sections, two dominant bacteria occur
in *Terua* n. sp. Guadeloupe. One is a sulfur-oxidizer closely related to various symbionts previously
280 identified in mussels. Its capability to perform sulfur oxidation is further supported by identification
of an APS reductase sequence displaying high similarity with those found in other SOX symbionts,
and by the identification of abundant sulfur in the gills in EDXs analysis. Sulfur-oxidizing
symbionts are reported in most *Bathymodiolinae* investigated to date in which they contribute to
nutrition and, arguably, to sulfide detoxification (Distel *et al.* 1988; Dubilier *et al.* 2008). The
285 second bacterium identified is a close relative of several *Colwellia* species. With a 16S rRNA
sequence similarity above 99%, it can confidently be classified within this genus. Ultrastructural
analysis indicates that bacteria are extracellular, a common feature of mussels associated with
organic falls (Gros and Gaill 2007; Duperron *et al.* 2008b). Clone libraries yielded similar amounts
of the two 16S rRNA phylotypes, and FISH confirmed that both were abundant with possible
290 dominance of the *Colwellia*-related bacterium in the investigated specimens. Both types of bacteria
are thus likely to play a significant role in the association. In a study of mussels from whale falls
near Japan, Fujiwara and colleagues also identified sulfur-oxidizing and *Colwellia*-related

(symbiont C) bacteria as extracellular symbionts in the gills of *Adipicola pacifica* (Fujiwara *et al.* 2010). The 16S rRNA sequence from the latter symbiont (AB539012) is only 93.2% similar to the
295 sequence reported herein and not its closest relative in the phylogenetic tree, and their FISH results indicated dominance of the sulfur-oxidizers. But overall it is reasonable to assume that the closely related *A. pacifica* and *Terua* n. sp. Guadeloupe which both live on whale carcasses share a similar type of dual symbiosis, different from the classical examples involving sulfur- and methane-oxidizers described in large vent and seep mussels (Fisher *et al.* 1993; Distel *et al.*, 1995). Whether
300 this unusual type of dual symbiosis is a peculiar feature of the *Terua* lineage or is strictly habitat-dependent needs to be further tested, notably on ESU T for which no data is currently available.

Potential significance of *Colwellia*-related bacterial symbionts in a dual symbiosis

The genus *Colwellia* currently comprises 13 described species, with many more sequences from
305 environmental samples reported in databases. *Colwellia* are adapted to cold marine environments, and include no known pathogen. The two closest described relatives of the *Terua* n. sp. Guadeloupe symbiont are *C. rossensis* and *C. psychroerythraea*. The latter is considered an obligate psychrophile with optimal growth at 8°C, congruent with recorded bottom water values (Methe *et al.* 2005). *Colwellia* are often reported attached to surfaces (Brinkmeyer *et al.* 2003) but the
310 occurrence of a flagellum suggests that if a highly similar bacterium occurs as a symbiont, it probably also has a free-living stage during which the flagellum is used. The presence of genes encoding a flagellum is reported from various environmentally-transmitted symbionts including the sulfur-oxidizing bacterium associated with the vent annelid *Riftia pachyptila* (Robidart *et al.* 2008). Both *Colwellia* species related to the *Terua* symbiont able to degrade organic compounds (Methe *et al.* 2005). The 5.37 Mb genome from *C. psychroerythraea* strain 34H has been sequenced and
315 possesses genes encoding various enzymes able to break down high molecular weight organic compounds. Many of these proteins seem to be extracellular. This capability could benefit the mussel host living on bone material, in particular inter-vertebrate disks, if we for example hypothesize a role in collagen degradation similar to what is reported for the *Osedax*-associated
320 Oceanospirillales symbionts (Goffredi *et al.* 2014). It can be noted that two *Colwellia* species were cultured from animals, namely *C. asteriadis* from the skin of a starfish (Choi *et al.* 2010) and *C. meonggei* from a sea squirt (Kim *et al.* 2013). Potential interaction with their host was not investigated, but given that the 16S rRNA sequence identified here is above 99% identical to that of cultivated *Colwellia* species, it might be possible to attempt cultivation of the *Terua* n. sp. symbiont,
325 should more become available in the future.

Conclusion

Terua n. sp. Guadeloupe is the first mussel species identified from whale fall ecosystems in the Antilles arc. Its absence from previous fauna samplings at various cold seeps in the Gulf of Mexico and western Atlantic suggests that it could be a true bone specialist, derived from ancestors found in the Pacific Ocean. Its dual symbiosis is unusual because most previously described bone-associated symbioses involved either only heterotrophic bacteria such as in the vestimentiferan *Osedax*, or sulfur-oxidizing autotrophs as in small mussels. Although the role of the *Colwellia*-related bacterium in the symbiosis is not ascertained, the fact that a similar dual symbiosis occurs in *Terua* n.sp. Guadeloupe 's relative *Adipicola pacifica* suggests that this could be a particular adaptation to bone habitats.

Acknowledgments

The material from Guadeloupe was obtained during the Karubenthos2 deep-sea cruise aboard ANTHEA funded by IRD and CNRS, and we thank Dr P. Bouchet and L. Corbari, the co-principal investigators, for their invitation. We thank P-Y Pascal for his participation in collecting the samples, the captain and crew of ANTHEA, and N. Léger for excellent technical assistance. We also thank the editor and two anonymous reviewers for comments that helped improve the manuscript. Molecular work was funded by a grant from 'Institut Universitaire de France' to SD.

Altschul SF, Gish W, Miller W *et al.* Basic local alignment search tool. *Mol Biol* 1990;**215**:403–10.

Baco-Taylor A. Food-web structure, succession, and phylogenetics on deep-sea whale skeletons. PhD dissertation, University of Hawaii at Manoa 2002.

Bartoli G, Sarnthein M, Weinelt M, Erlenkeuser H, Garbe-Schönberg D, Lea DW. Final closure of Panama and the onset of northern hemisphere glaciation. *Earth Planet Sci Lett* 2005;**237**:33-44.

Brinkmeyer r., Knittel K, Jurgens J *et al.* Diversity and structure of bacterial communities in Arctic versus Antarctic pack ice. *Appl Env Microbiol* 2003;**69**:6610–9.

Choi EJ, Kwon HC, Koh HY *et al.* *Colwellia asteriadis* sp. nov., a marine bacterium isolated from the starfish *Asterias amurensis*. *Int J Syst Evol Microbiol* 2010;**60**:1952–7.

Cole JR, Wang Q, Cardenas E *et al.* The ribosomal database project: improved alignments and new tools for rRNA analysis. *Nucl Acids Res* 2009;**37**.

Colgan DJ, McLauchlan A, Wilson GDF *et al.* Histone H3 and U2 snRNA DNA sequences and arthropod molecular evolution. *Aust J Zool* 1998;**46**:419–37.

- Deming JW, Reysenbach AL, Macko SA *et al.* Evidence for the microbial basis of a chemoautotrophic invertebrate community at a whale fall on the deep seafloor: bone-colonizing bacteria and invertebrate endosymbionts. *Miscrosc Res Tech* 1997;**37**:162–70.
- Distel D, Lane D, Olsen G *et al.* Sulfur-oxidizing bacterial endosymbionts - Analysis of phylogeny and specificity by 16S ribosomal RNA sequences. *J Bacteriol* 1988;**170**:2506–10.
- Distel DL, Lee HKW, Cavanaugh CM. Intracellular coexistence of methano- and thioautotrophic bacteria in a hydrothermal vent mussel. *Proc Natl Acad Sci USA* 1995;**92**:9598–602.
- Dubilier N, Bergin C, Lott C. Symbiotic diversity in marine animals: the art of harnessing chemosynthesis. *Nat Rev Microbiol* 2008;**6**:725–40.
- Duperron S. The diversity of deep-sea mussels and their bacterial symbioses. In: Kiel S (ed.). *The Vent and Seep Biota*. Springer, 2010, 137–67.
- Duperron S, Halary S, Lorion J *et al.* Unexpected co occurrence of 6 bacterial symbionts in the gill of the cold seep mussel *Idas* sp. (Bivalvia: Mytilidae). *Env Microbiol* 2008a;**10**:433–45.
- Duperron S, Laurent MCZ, Gaill F *et al.* Sulphur-oxidizing extracellular bacteria in the gills of Mytilidae associated with wood falls. *FEMS Microbiol Ecol* 2008b;**63**:338–49.
- Duperron S, Nadalig T, Caprais JC *et al.* Dual symbiosis in a *Bathymodiolus* mussel from a methane seep on the Gabon continental margin (South East Atlantic): 16S rRNA phylogeny and distribution of the symbionts in the gills. *Appl Env Microbiol* 2005;**71**:1694–700.
- Duperron S, Sibuet M, MacGregor BJ *et al.* Diversity, relative abundance, and metabolic potential of bacterial endosymbionts in three *Bathymodiolus* mussels (Bivalvia: Mytilidae) from cold seeps in the Gulf of Mexico. *Env Microbiol* 2007;**9**:1423–38.
- Eilers H, Pernthaler J, Glöckner FO *et al.* Culturability and In Situ abundance of pelagic bacteria from the North Sea. *Appl Environ Microbiol* 2000;**66**:3044–51.
- Faure B, Schaeffer SW, Fisher CR. Species distribution and population connectivity of deep-sea mussels at hydrocarbon seeps in the Gulf of Mexico. *Plos One* 2015;**10**:e0118460.
- Fisher CR, Brooks JM, Vodenichar JS *et al.* The co-occurrence of methanotrophic and chemoautotrophic sulfur oxydixing bacterial symbionts in a deep-sea mussel. *Mar Ecol* 1993;**14**:277–89.
- Folmer O, Black MB, Hoeh WR *et al.* DNA primers for amplification of mitochondrial cytochrome C oxidase subunit I from metazoan invertebrates. *Mol Mar Biol Biotechnol* 1994;**3**:294–9.
- Fujiwara Y, Kawato M, Noda C *et al.* Extracellular and mixotrophic symbiosis in the whale-fall mussel *Adipicola pacifica*: a trend in evolution from extra- to intracellular symbiosis. *PLOS One* 2010;**5**:e11808.
- Gaudron SM, Demoyencourt E, Duperron S. Reproductive traits of the cold seep mussel *Idas modiolaeformis*: from gametogenesis to larvall dispersal. *Biol Bull* 2012;**222**:6–16.
- Goffredi SK, Yi H, Zhang Q *et al.* Genomic versatility and functional variation between two dominant heterotrophic symbionts of deep-sea *Osedax* worms. *Isme J* 2014;**8**:908–24.

- Gros O, Gaill F. Extracellular bacterial association in gills of “wood mussels.” *Cah Biol Mar* 2007;**48**:103–9.
- Gustafson R, Turner R, Lutz R *et al.* A new genus and five new species of mussels (Bivalvia, Mytilidae) from deep-sea sulfide/hydrocarbon seeps in the Gulf of Mexico. *Malacologia* 1998;**40**:63–112.
- Hassouna N, Michot B, Bachellerie J. The complete nucleotide-sequence of Mouse 28S ribosomal-RNA gene - Implications for the process of size increase of the large subunit ribosomal-RNA in higher Eukaryotes. *Nucleic Acids Res* 1984;**12**:3563–83.
- Kim Y-O, Park S, Nam B-H *et al.* *Colwellia meonggei* sp. nov., a novel gammaproteobacterium isolated from sea squirt *Halocynthia roretzi*. *Antonie Van Leeuwenhoek* 2013;**104**:1021–7.
- Laming SR, Duperron S, Cunha MR *et al.* Settled, symbiotic, then sexually mature: adaptive developmental anatomy in the deep-sea, chemosymbiotic mussel *Idas modiolaeformis*. *Mar Biol* 2014;**161**:1319–33.
- Laming SR, Duperron S, Gaudron SM *et al.* Adapted to change: The rapid development of symbiosis in newly settled, fast-maturing chemosymbiotic mussels in the deep sea. *Mar Environ Res* 2015a;**112**:100–12.
- Laming SR, Szafranski KM, Rodrigues CF *et al.* Fickle or Faithful: The roles of host and environmental context in determining symbiont composition in two Bathymodioline Mussels. *Plos One* 2015b;**10**:e0144307.
- Lane D. 16S/23S rRNA sequencing. *Nucleic Acid Techniques in Bacterial Systematics*. New York: Stakebrandt E. and Goodfellow M. (Eds), John Wiley and Sons, 1991, 115–75.
- Lorion J, Buge B, Cruaud C *et al.* New insights into diversity and evolution of deep-sea Mytilidae (Mollusca: Bivalvia). *Mol Phyl Evol* 2010;**57**:71–83.
- Lorion J, Kiel S, Faure B *et al.* Adaptive radiation of chemosymbiotic deep-sea mussels. *Proc Biol Sci* 2013;**280**, DOI: 10.1098/rspb.2013.1243.
- Methe BA, Nelson KE, Deming JW *et al.* The psychrophilic lifestyle as revealed by the genome sequence of *Colwellia psychrerythraea* 34H through genomic and proteomic analyses. *Proc Natl Acad Sci U S A* 2005;**102**:10913–8.
- Meyer B, Kuever J. Molecular analysis of the distribution and phylogeny of dissimilatory adenosine-5'-phosphosulfate reductase-encoding genes (aprBA) among sulfur-oxidizing prokaryotes. *Microbiology* 2007;**153**:3478–98.
- Ratnasingham S, Hebert PDN. BOLD: The Barcode of Life Data System (www.barcodinglife.org). *Mol Ecol Notes* 2007;**7**:355–64.
- Robidart JC, Bench SR, Feldman RA *et al.* Metabolic versatility of the *Riftia pachyptila* endosymbiont revealed through metagenomics. *Env Microbiol* 2008;**10**:727–37.
- Southward EC. The morphology of bacterial symbioses in the gills of mussels of the genera *Adipicola* and *Idas* (Bivalvia : Mytilidae). *J Shellfish Res* 2008;**27**:139–46.

Thubaut J, Puillandre N, Faure B *et al.* The contrasted evolutionary fates of deep-sea chemosynthetic mussels (Bivalvia, Bathymodiolinae). *Ecol Evol* 2013;**3**:4748–66.

Won YJ, Jones WJ, Vrijenhoek RC. Absence of cospeciation between deep-sea mytilids and their thiotrophic symbionts. *J Shellfish Res* 2008;**27**:129–38.

Yu Y, Li H, Zeng Y *et al.* Phylogenetic diversity of culturable bacteria from Antarctic sandy intertidal sediments. *Polar Biol* 2010;**33**:869–75.

Table legends :

Table 1 : PCR primers, cycling conditions (temperature and number of cycles) and number of clones analyzed for each of the genes sequenced from *Terua* n. sp. Primers were obtained from : (Hassouna *et al.*, 1984; Lane 1991; Folmer *et al.* 1994; Colgan *et al.* 1998; Baco-Taylor 2002; Meyer and Kuever 2007; Ratnasingham and Hebert 2007; Duperron *et al.* 2008a)

Figure legends:

350 **Figure 1. Structural analysis of mussel specimens collected from sunken whale inter-vertebral disk.** **A:** Light micrograph of a freshly collected mussel at a depth of 800m. The shell appears smooth with a visible pink prodissoconch located at the umbo (arrow). **B:** ESEM image obtained from a piece of gill not dehydrated with solvents, showing seven gill filaments (G) attached to the gill axis (Gs). **C:** EDX spectrum obtained from one of these gill filaments showing a peak of
355 elemental sulfur (11 times higher than in EDX spectra obtained from mantle or foot [D]) suggesting that gill filaments harbor sulfur-oxidizing bacteria (C: carbon, Ca: calcium, Cl: chloride, Na: sodium, Mg: magnesium, O: oxygen, P: phosphorous, S: elemental sulfur). E: SEM views show the faint marginal groove (arrows) along the ventral edge of the gill and the numerous cilia on the frontal surface (E-F). F: Just below the ciliated zone of each gill filament (ZC), some bacteria could
360 be observed (arrows) attached to the apical pole of the cells forming the lateral zone (ZL) of each gill filament.

Figure 2: SEM views of larval shell morphology. **A:** The larval shells (appearing in pink in Fig.1A) correspond to a small prodissoconch I (PI delineated by a white dot line) and a larger
365 prodissoconch II (P II) with a total mean length of 445µm. In adult individuals, the umbo is curved and prevents the observation of the prodissoconch I. The separation between prodissoconch II and the adult shell (dissoconch, D) is obvious. **B:** In a lateral view, the numerous tight growth lines of the prodissoconch II clearly suggests a lengthy planktotrophic larval development. The metamorphic line separating prodissoconch and dissoconch (D) is indicated by straight arrows
370 while the periphery of the prodissoconch I is delineated by a dot line. **C:** In this dorsal view, once the right valve is removed, the small prodissoconch I (dot line) appears smooth while the larval shell (P II) is characterized by numerous concentric growth lines. **D:** Higher magnification focusing on the metamorphic line (arrows) that delineates the dissoconch characterized by smoother growth lines compared to the prodissoconch II. Prodissoconch I (PI); prodissoconch II (PII); dissoconch
375 (D).

Figure 3 : Phylogeny of Bathymodiolinae based on concatenate sequences of fragments of genes encoding mtCOI, mt16S rRNA and histone H3. A total of 1099 nucleotide positions were analyzed, positions with gaps and missing data were removed. A ML approach was used (see
380 material and methods for detail). Scale bar represents 20% estimated sequence divergence. Only bootstrap values above 60 are displayed. The clade where sequences from this study cluster (in bold) and corresponding to the genus *Terua* sensu Thubaut 2013 is emphasized. Accession numbers of sequences used for this reconstruction are summarized in supplementary material S1.

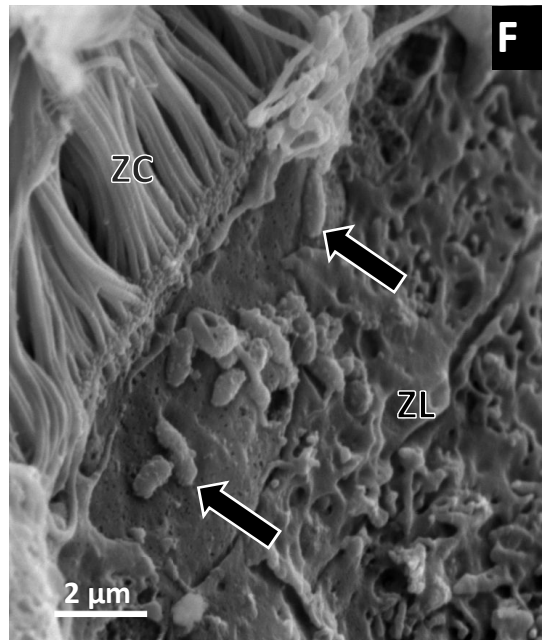
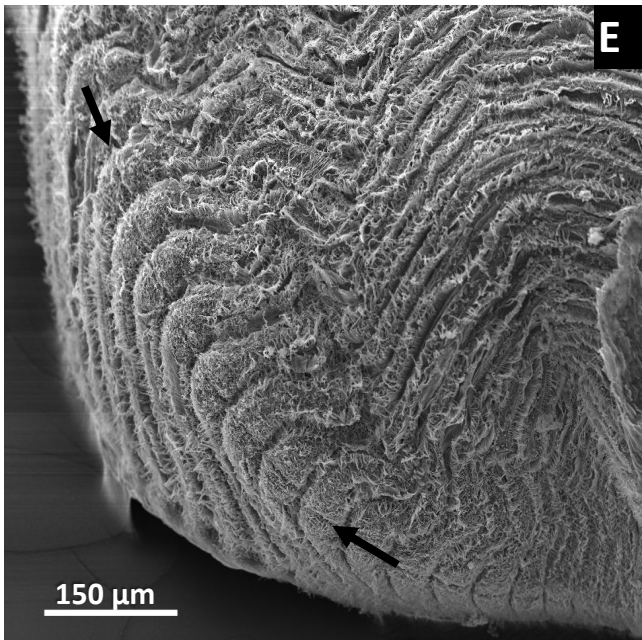
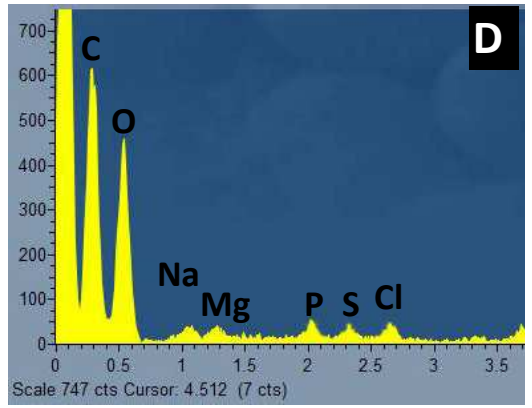
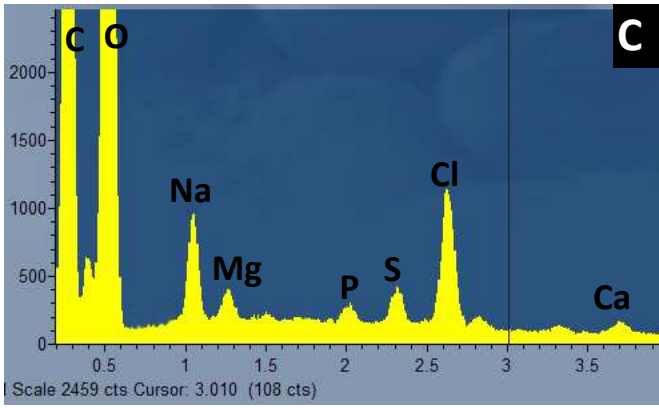
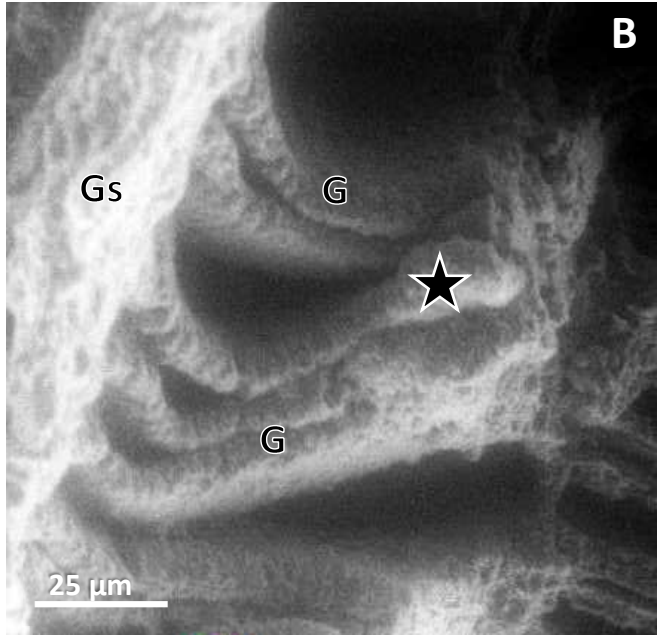
Figure 4. Ultrastructural analysis (TEM) of the gill filaments. **A:** The ciliated zone of the gill filaments is free of bacteria and classically organized with several ciliated cells. This ciliated zone consists of a simple epithelium, which is in contact with a connective axis (CA), with cells harboring frontal cilia (F), latero-frontal cilia (LF), and lateral cilia (L). Fibroblasts (Fb). **B:** The lateral zone of each gill filament is organized as a pseudostratified epithelium organized around its
390 blood lacuna (BL). Each epithelial cell (BC) harbors numerous bacteria (arrows) throughout the lateral zone of the gill filament. **C:** Higher magnification of the lateral zone focusing on two bacteriocytes. The various bacterial shapes observed (rod-shaped or ovoid-shaped figures) could be due to the section orientation. Note that two morphotypes are observable, one displaying higher density in the periphery of the cells (one almost black, the other one gray). Extracellular bacteria are
395 located on the apical surface of the host cells in contact with microvilli (arrows). Bacteria are observed outside the bacteriocytes but also inside vacuoles (stars), each of which contains numerous bacteria with a shape similar to that of extra cellular ones. These bacteria probably became enclosed in the vacuoles by phagocytosis of extracellular bacteria. N: nucleus of the host cell.

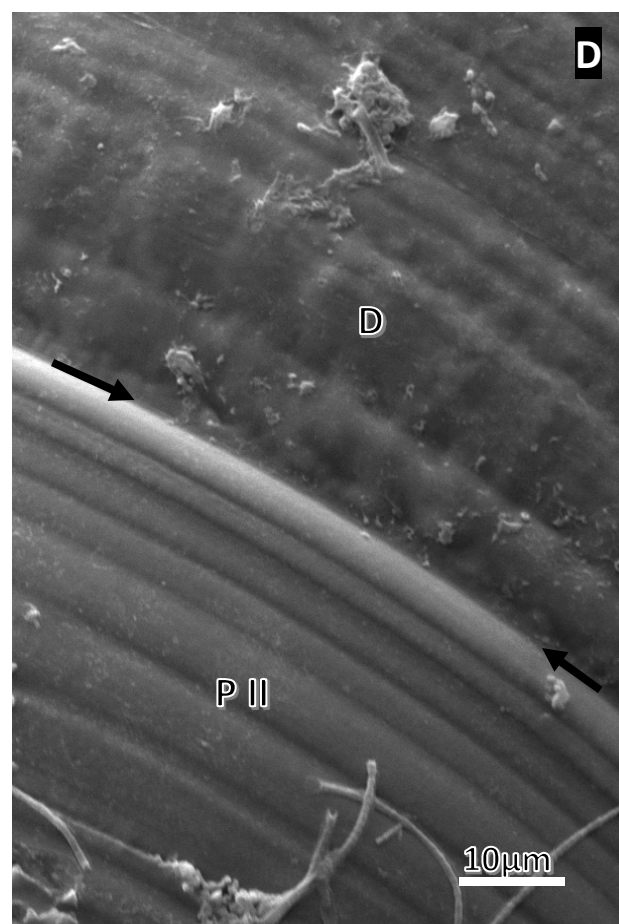
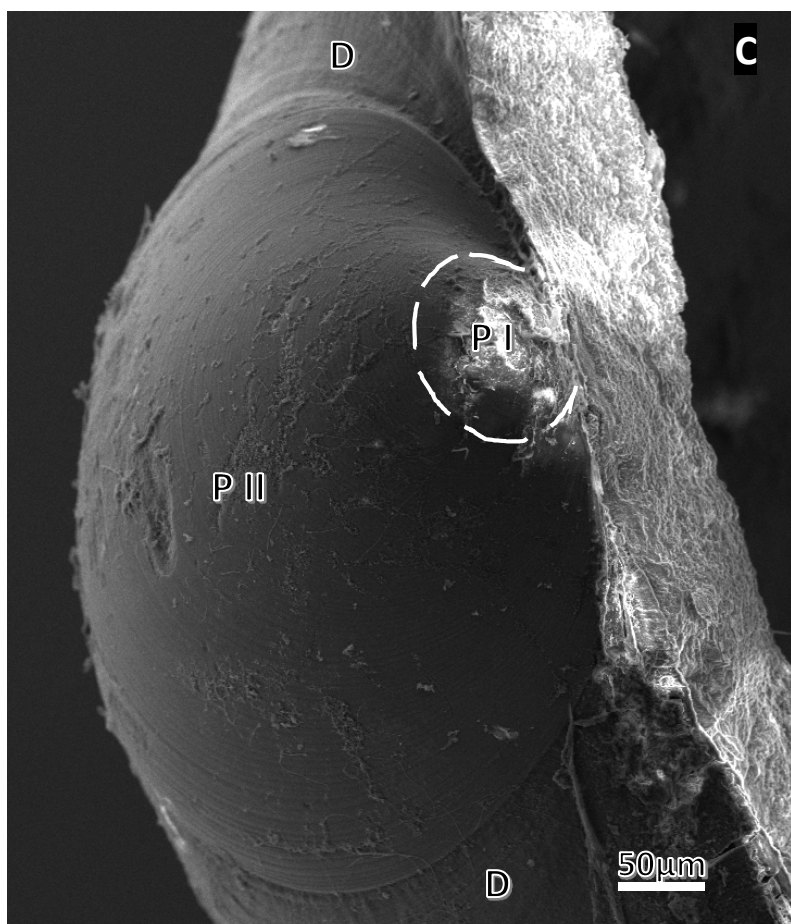
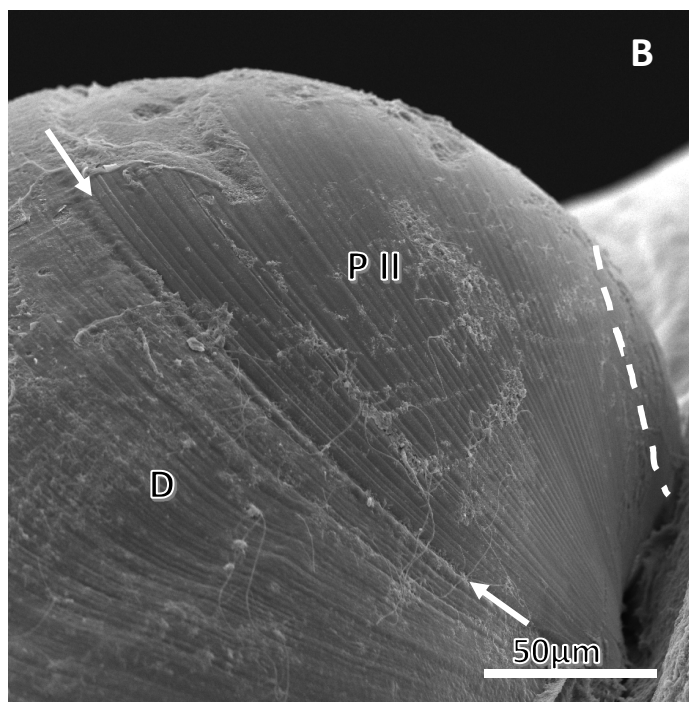
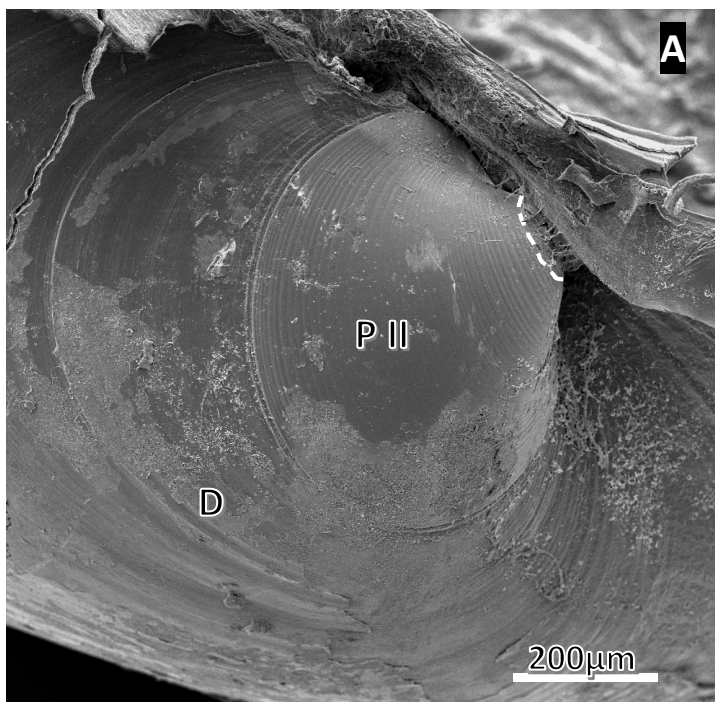
Figure 5. Ultrastructural analysis of the bacteriocytes. **A-C:** The cytoplasm of the bacteriocytes contains residual bodies, characterized by whorls of membranes (stars), probably resulting from the intracellular digestion of extracellular bacteria as previously described in wood-mussels (Gros and Gaill, 2007). In these TEM views, most of the bacteria seem to be intracellular due to their location within large vacuoles resulting of phagocytosis. **B:** The first bacteriocyte (BC) of the lateral zone in
405 contact with the last eulateral cell (EL) harbors only extracellular bacteria (arrows) located between the microvilli (mv). **C:** microvilli (arrows) are obvious inside the vacuole containing numerous bacteria, some of them dividing. Note the two bacterial morphotypes easily distinguishable (**A, C**); a dark one (asterisks) with a black periphery of the bacterial cell and a clearer one (white triangles). BL: blood lacuna. N; nucleus of host cells.

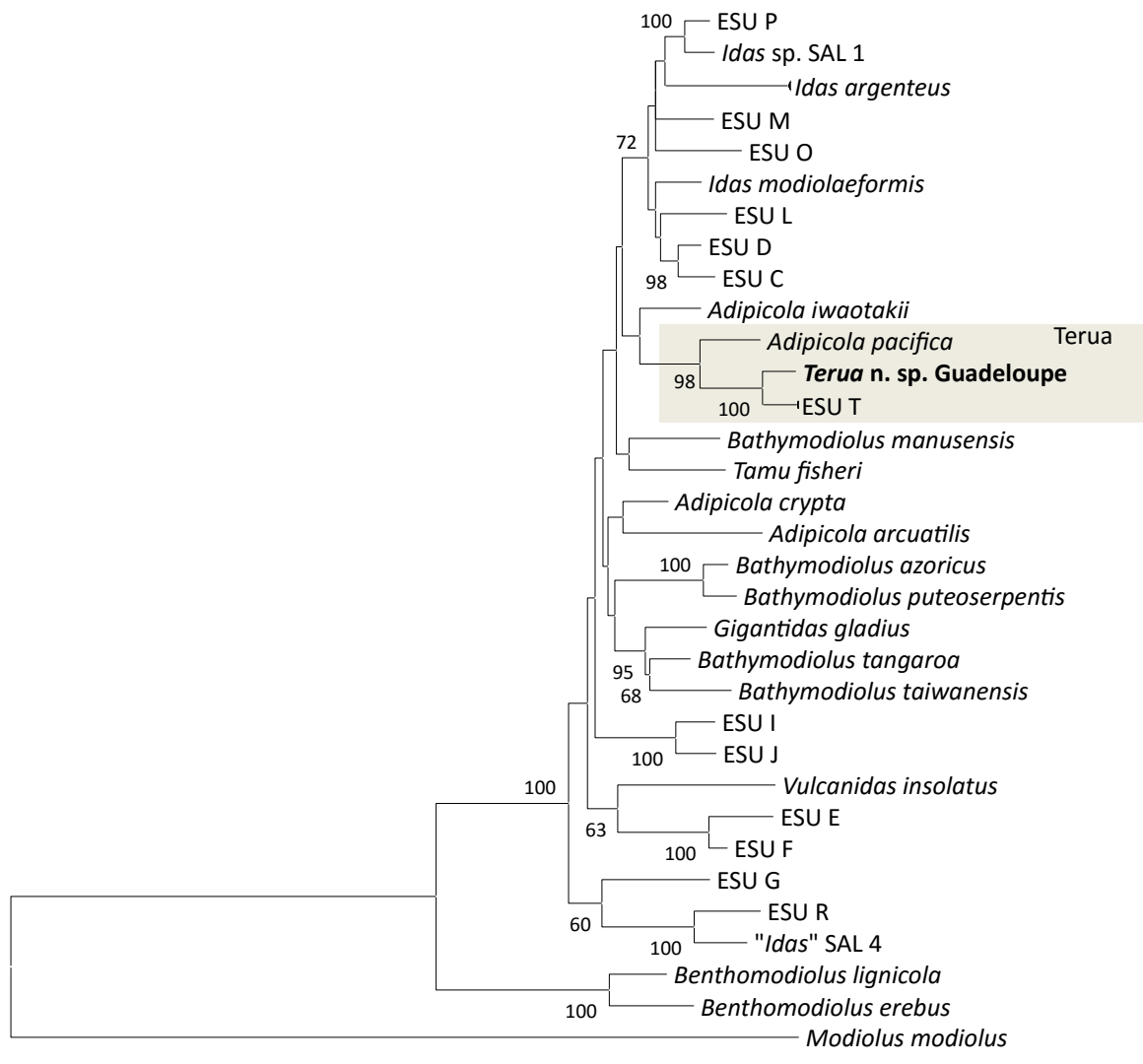
Figure 6: Phylogeny based on 16S rRNA-encoding gene sequences from bacterial symbionts associated with Bathymodiolinae. Names refer to the host species, clades comprising sulfur-oxidizing, methane-oxidizing, methylotroph-related, and *Colwellia*-related bacteria are indicated. A total of 1197 nucleotide positions were analyzed. See materials and methods for detail. Scale bar represents 5% estimated sequence divergence. Bootstrap values above 60 are displayed. Sequences from this study in bold.

Figure 7: Fluorescence *in situ* hybridization on sections of gill filaments of *Terua n. sp. Guadeloupe*. Signal from probe Bthio-193 is in green in pictures A to D (Cy-3 labelled in A-B, Cy-5 labelled in C-D). Signal from probe Eub-338 is in red in A and B (Cy-5 labelled), signal from probe Alt1413 is in red in C and D (Cy-3 labelled). DAPI appear in blue in B and C. **A-B:** overview of several gill filaments, bacteria appear in red, sulfur-oxidizers in green or yellow. **C-D:** detail of gill filaments. Sulfur-oxidizing symbionts appear in green, *Colwellia*-related symbionts in red. Note the coexistence of the two symbionts in the gills. Scale bars represent 100 μm (**A**) and 25 μm (**B-D**).

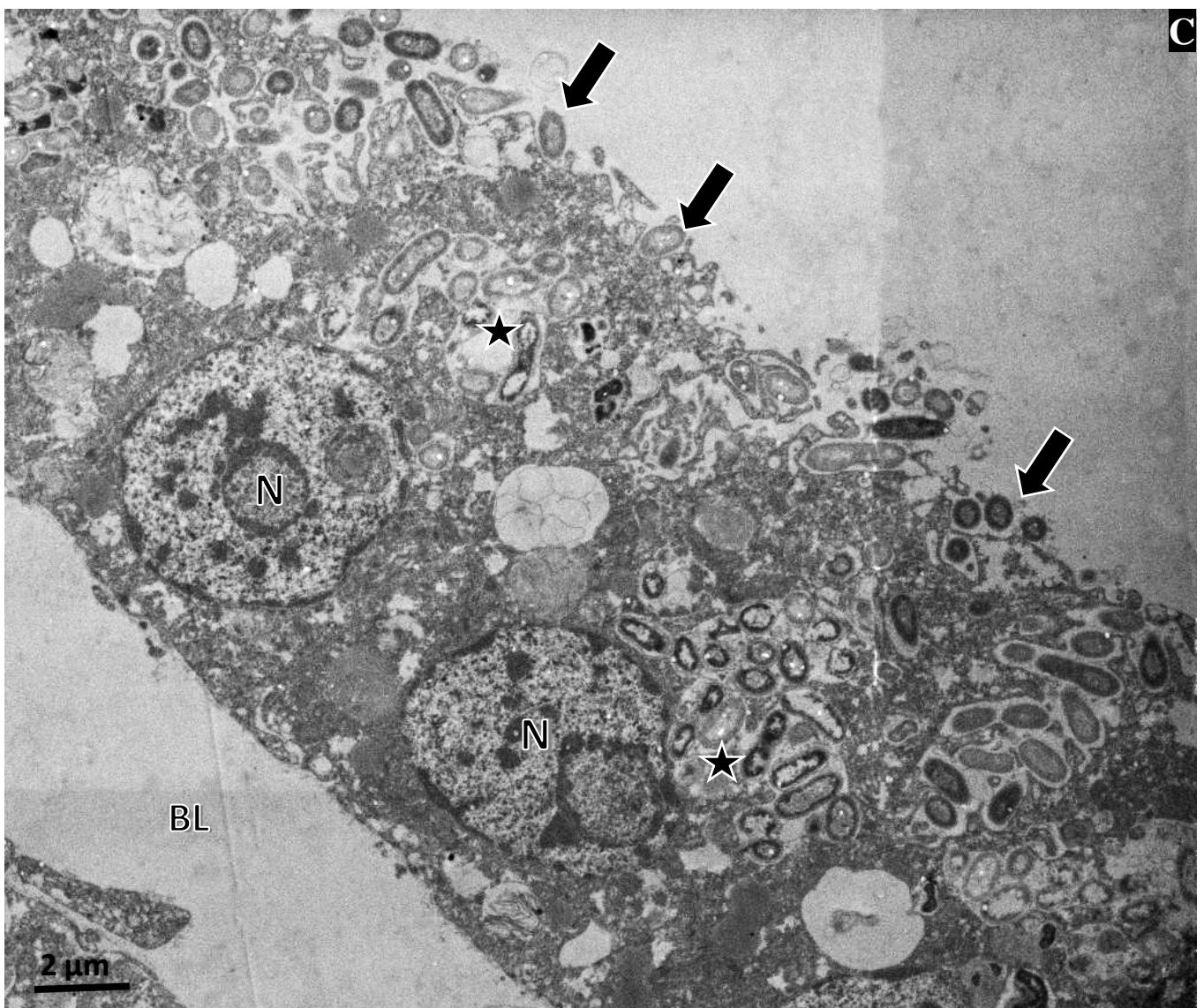
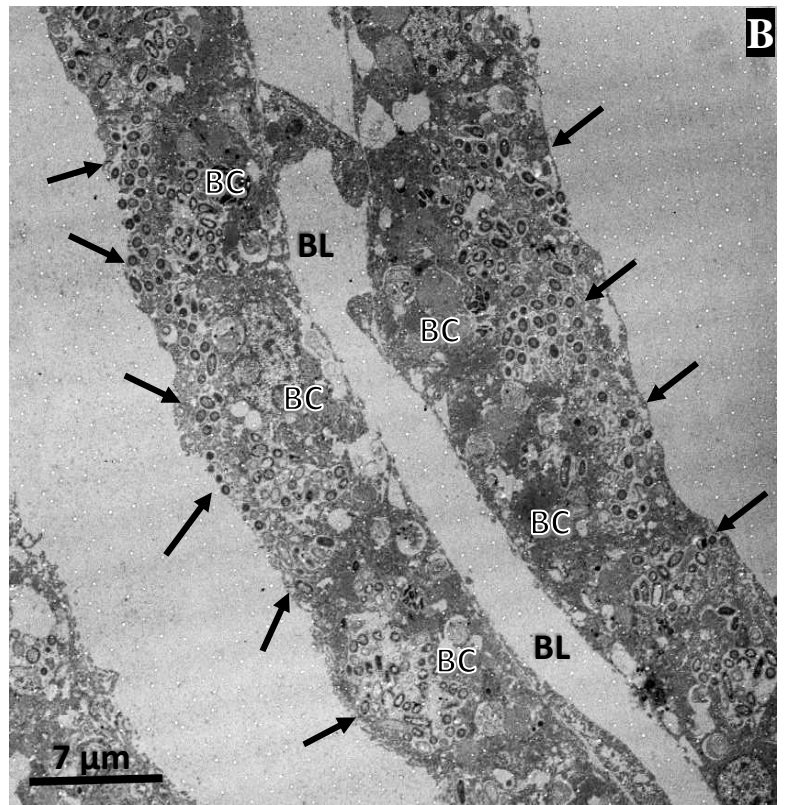
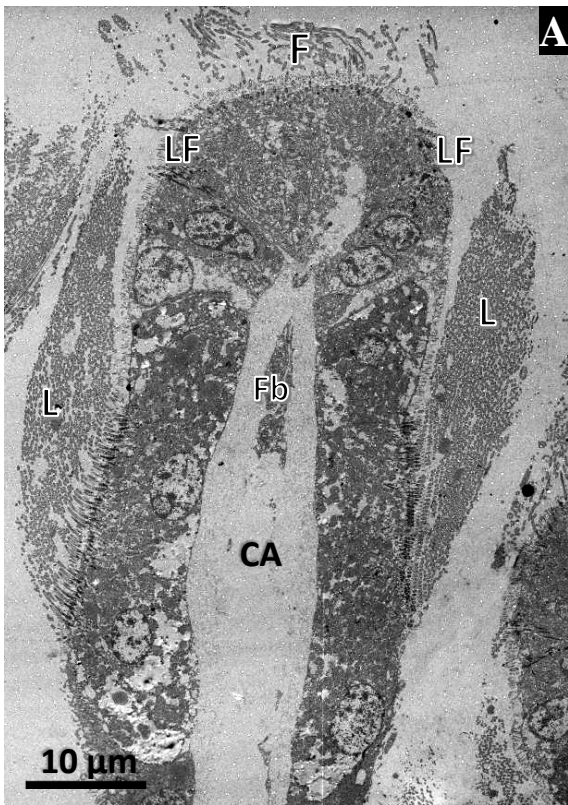
Supplementary material S1: accession numbers of gene sequences used in the phylogenetic tree displayed on figure 3.

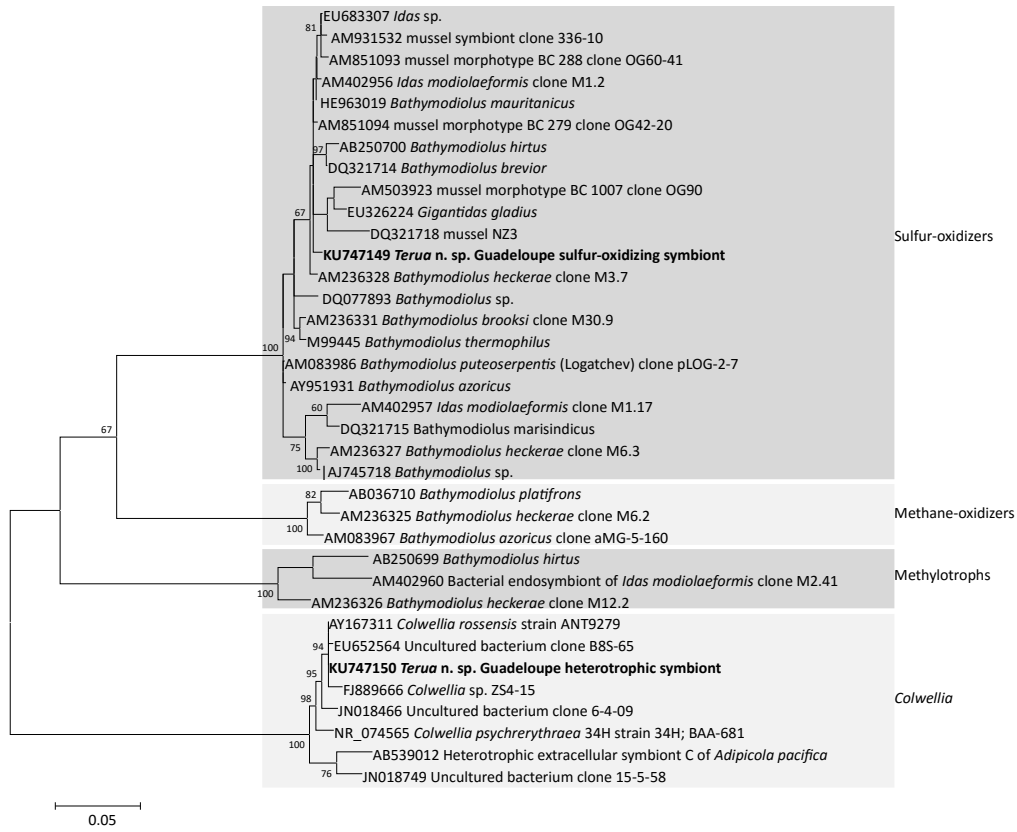


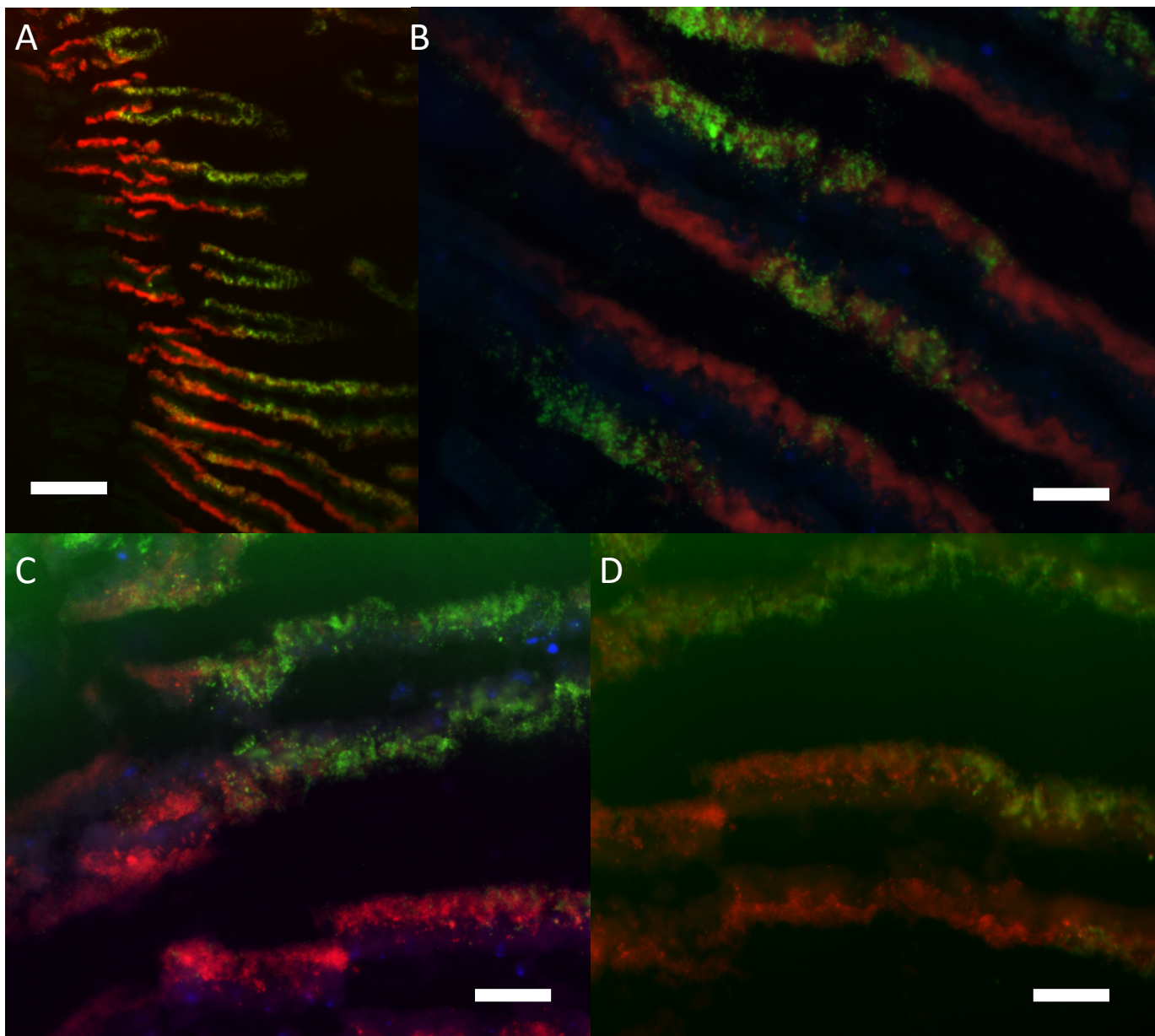




0.2







	Gene	T(°C) and cycles	Primer names	Primer sequences (5'→3')	seq length (nt)	Reference	clones analyzed
Host	COI mtDNA	50°C (35)	H691	GTRTTAAARTGRCGATCAAAAAT	627	Duperron et al 2008 Folmer et al. 1994	6
			LCO1490	GGTCAACAAATCATAAAGATATTGG			
	28S rRNA	55°C (35)	C1prime	ACCCGCTGAATTTAAGCAT	1128	Hassouna et al. 1984 Hassouna et al. 1984	9
			C4	TCGGAGGGAACCAGCTACTA			
mt16S rRNA	55°C (35)	16SA	GGARGTASGCCCTGCCCWATGC	466	Baco-Taylor 2002 Ratnasingham 2007	7	
		LRJ	CTCCGGTTTGAACCTCAGATCA				
H3	57°C (35)	F1	ATGGCTCGTACCAAGCAGACVGC	351	Colgan 1998 Colgan 1998	12	
		R1	ATATCCTTRGGCATRATRGTGAC				
Bacteria	16S rRNA	48°C (31)	27F	AGAGTTTGATCCTGGCTCAG	~1500	Lane 1991 Lane 1991	271
			1492R	GGTTACCTTGTTACGACTT			
	APS	60°C (30)	APS1-FW	TGGCAGATCATGATYMYGG	Meyer Kuever 2007 Meyer Kuever 2007	21	
		APS4-RV	GCGCCAACYGGRCRTA				

Genus	Species	mtCOI	28S	mt16S	H3	Ocean
<i>Modiolus</i>	<i>modiolus</i>	FJ890501	EF526455	KF611732	KF720595	Atlantic
<i>Benthomodiolus</i>	<i>lignicola</i>	AY275545	AY781131	KF611733	KF720596	Western Pacific
<i>Benthomodiolus</i>	<i>erebus</i>	KF611694	KF611699	KF611734	KF720597	Northeast Pacific
	ESU E	FJ937079	GU065791	KF611736	KF720598	Western Pacific
	ESU F	FJ937127	GU065809	KF611737	KF720599	Western Pacific
<i>Vulcanidas</i>	SAL3	DQ340772	DQ863946	KF611738	KF720600	Western Pacific
<i>Vulcanidas</i>	<i>insolatus</i>	FJ767936	FJ767937	KF611739	KF720601	Western Pacific
<i>Tamu</i>	<i>fisheri</i>	AY649803	AY781132	HF545065	HF545148	Gulf of Mexico
	SAL4	DQ340776	DQ863947	KF611741	KF720603	Western Pacific
	ESU R	FJ937239	GU065877	KF611742	KF720604	Western Pacific
	ESU G	FJ937161	GU065778	KF611744	KF720606	Western Pacific
<i>Bathymodiolus</i>	<i>taiwanensis</i>	GU966638	GU966641	KF611746	KF720608	Western Pacific
<i>Bathymodiolus</i>	<i>tangaroa</i>	AY608439	AY781149	KF611748	KF720610	Western Pacific
<i>Gigantidas</i>	<i>gladius</i>	AY649802	AY781134	HF545085	HF545174	Western Pacific
<i>Adipicola</i>	<i>crypta</i>	EU702319	EU683298	KF611750	KF720612	Western Pacific
<i>Nypamodiolus</i>	<i>longissimus</i>	DQ340773	DQ863945	KF611752	KF720614	Western Pacific
	ESU J	FJ937189	GU065842	KF611753	KF720615	Western Pacific
	ESU I	FJ937188	GU065774	KF611754	KF720616	Western Pacific
<i>Bathymodiolus</i>	<i>manusensis</i>	GU966637	GU966642	HF545059	KF720618	Western Pacific
<i>Adipicola</i>	<i>arcuatilis</i>	FJ937033	GU065879	KF611756	KF720619	Western Pacific
<i>Terua</i>	ESU T	FJ937283	GU065804	KF611757	KF720620	Western Pacific
<i>Bathymodiolus</i>	<i>puteoserpentis</i>	AY649796	AY781151	HF545053	HF545163	Mid-Atlantic Ridge
<i>Bathymodiolus</i>	<i>azoricus</i>	AY649795	AY781148	KF611758	KF720621	Mid-Atlantic Ridge
<i>Idas</i>	SAL 1	DQ340775	DQ863944	KF611761	KF720624	Western Pacific
	ESU P	FJ937222	GU065846	KF611762	KF720625	Western Pacific
	ESU O	FJ937211	GU065763	KF611763	KF720626	Western Pacific
	ESU D	EU702357	EU683275	KF611765	KF720628	Western Pacific
	ESU C	EU702376	EU683260	KF611766	KF720629	Western Pacific
	ESU M	FJ937202	GU065845	KF611767	KF720630	Western Pacific
	ESU L	FJ937193	GU065767	KF611768	KF720631	Western Pacific
<i>Adipicola</i>	<i>pacifica</i>	HF545115	HF545040	HF545066	HF545161	Western Pacific
<i>Adipicola</i>	<i>iwaotakii</i>	EU702333	EU683288	KF611770	KF720633	Western Pacific
<i>Idas</i>	<i>modiolaeformis</i>	FJ158585	FJ159555	KF611772	KF720635	Eastern Atlantic, Mediterranean
<i>Idas</i>	<i>argenteus</i>	LM992892	LM992896	LM992901	LM992897	Atlantic
<i>Terua</i>	n. sp.	KU747147	KU747145	KU747146	KU747148	Antilles Arc
Genus	Species	mtCOI	28S	mt16S	H3	Ocean