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# Genomic clues of chemosynthetic symbioses from deep-sea seep-living *Lamellibrachia*

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## Abstract

Since the discovery of chemosynthetic symbiosis in hydrothermal vents and cold seeps, the genetic mechanism of how organisms maintain the unique host-symbiont associations at the celluar level is still mostly unknown. The gutless tubeworm *Lamellibrachia* represents one of the longest-lived invertebrates and is widespread in many deep-sea cold seeps, providing an excellent model to study mechanisms like host-symbiont association, adaptation to chemosynthetic environments and longevity. However, the genomic and molecular evolutionary information of hosts is exceptionally scarce. Here, we characterized the genome of *Lamellibrachia* *lumysi*. We found evidence that symbionts may compensate for the host’s deficiency in amino acid biosynthesis. Unexpectedly, we found large expansion of hemoglobin B1 sequences and many of them also possess a free cysteine which hypothesized to function as sulfide-binding. Moreover, we found no evidence that sufide-binding is mediated by zinc ions across tubeworms, suggesting the hemoglobin structure and suflide binding mechanism is potentially more complex than previously thought. Our comparative analyses detected that TLR4-like/MYD88 pathway might be essential to host immunity and in response to symbionts and pathogens. Last, we identified a list of genes potentially related to longevity and cell cycles. Thus, these results help elucidate previously unknown links and potential mechanisms related to the evolution of holobionts, adaptations to extreme environments andare likely extend to other chemosynthetic holobionts.

## Introduction



**Fig 1.** *Lamellibrachia* from seep localities in Gulf of Mexico.

Since the discovery in the 1980s, siboglinid tubeworms at hydrothermal vents and cold seeps have fascinated evolutionary biologists for their unique symbiosis between the worms and chemosynthetic symbionts. However, the genetic mechanism of how organisms maintain the novel host-symbiont associations at the cellular level is still mostly unknown. The vestimentiferan tubeworm *Lamellibrachia* *lumysi* distributed along the Gulf of Mexico is one of the most dominant taxa living in deep-sea cold seeps. At some seeps the vestimentiferan tubeworms are so abundant that they form a unique habitat that is attractive for other species (Fig 1), maintaining alpha and beta biodiversity and thus facilitating adaptive radiations and evolutionary novelies. Siboglinids typically lack a digestive tract and rely on sulfide-oxidizing bacterial symbionts for nutrition. Hosts acquire their symbionts from the surrounding environment and store them in a specialized tissue called the trophosome (Nussbaumer, Fisher, and Bright 2006). Previous studies suggested that vestimentiferan chemoautotrophic symbionts can use both rTCA and Calvin cycle for carbon fixation as a nutrient source for the hosts. However, previous metabolic and physiological studies primarily focus on symbionts associated with host lineages, how exchanges of nutritions and metabolites between two partners from the host perspective are still lacking.

One of the key adaptations to the remarkable ability of tubeworms to thrive in chemosynthetic habitats is that siboglinid hemoglobins (HBs) can bind oxygen and sulfide simultaneously and reversibly at two different sites [@@zal1996multi]. To avoid the toxic effects of sulfide while supplying it to their chemoautotrophic endosymbionts, siboglinids possesses a multi hemoglobin system with three different extracellular hemoglobins (Hbs; V1, V2, and C1): two dissolved in the vascular blood, V1 and V2, and one in the coelomic fluid, C1 (Arp and Childress 1981, @zal1996multi). Siboglinid Hbs consist of four heme-containing chains (A1, A2, B1, B2). Sulfur-binding capabilities are hypothesized to be due to free cysteine residues at key positions in Hbs, especially in the A2 and B2 chains (Zal et al. 1997). V1 Hb can form persulfide groups on its four linker chains (L1-L4), a mechanism that can account for the higher sulfide-binding potential of this Hb (Zal et al. 1997). However, another study found no evidence of the first hypothesis and suggested sulfid-binding affinity was mediated by the zinc moieties bound to amino acid residues at the interface between pairs of A2 chains in *Riftia* (Flores et al. 2005). Thus, it is still not clear which mechanism is primarily responsible for sulfide-binding in siboglinids.

In contrast with one of the fastest growing vent-living relatives (Lutz et al. 1994), seep-living vestimentiferans are thought to be the most long-lived non-colonial marine invertebrates. It requires between 170 and 250 years to grow to a length up to two meters (Bergquist, Williams, and Fisher 2000). The immunity function is no doubt the critical evolutionary driver of maintaining symbiosis and has important implications in ageing, and is also critical for organisms being held in high densities in chemosynthetic environments. However, very little is known in genetic mechanisms related to immunity in most chemosynthetic host species, and it is far more complex in some group of invertebrates than traditionally recognized from recent studies (Halanych and Kocot 2014) (Tassia, Whelan, and Halanych 2017). Thus, *Lamellibrahcia* provides an excellent model to study immunity function associated with host-symbiont relationships and adaptations to chemosynthetic habitats. However, the genomic and molecular evolution information on *Lamellibrachia* is exceptionally scarce.

Considerable debate persists concerningthe evolutionary origins of siboglinids, owing to conflicting theories of its origins from fossil and molecular age estimates. Siboglinids have been claimed to be as old as 430 MYA based on fossil tubes found in the Silurian fossil vent communities (Little 2002), but molecular clock analyses suggest a much recent (50-126MYA) origin based on COI or 16S sequences (Little and Vrijenhoek 2003). Recently, Late Cretaceous *Osedax* fossil traces on reptile falls provides a solid calibration point for the molecular clock of the siboglinids (~100 MYA) (Danise and Higgs 2015). Moreover, a detailed chemical and morphological analyses of tubes from the Figueroa deposits were made by vestimentiferans, which significantly extends the age of this lineage than previous molecular clock analyses (Georgieva et al. 2017).

Here, we described the genomic, transcriptomic and proteomic sequencing and comparative genomic analysis of tubeworm *Lamellibrachia* collected from the Gulf of Mexico. Our genomic studies reveal new genetic information on the evolution and of *Lamellibrachia* and provide genetic pathway and novel candidate genes that might underlie the extraordinary characteristics of tubeworm, including nutrition mode, immunity function, hemoglobin evolution, and longevity. Moreover, we also conducted a detailed molecular clock analysis to discern the previous debates concerning the evolutionary origins of siboglinids. The findings provide hitherto previously unknown evidence of genetic machinery related to tubeworm success in deep-sea chemosynthytic communities, such as vents and seeps.

## Methods

Scripts and data for the analyses are available in a git repository at <https://github.com/yzl0084/Lamellibrachia-genome>.

### Biological materials.

Adult *Lamellibrachia* *lumysi* specimens were collected from seep localities in the Mississippi Canyon at 754 m depth in the Gulf of Mexico (N 28°11.58’, W 89°47.94’), using the R/V Seward Johnson and Johnson Sea Link in October 2009. All samples were frozen at 80˚C following collection.

### Genome sequencing and assembly.

Vestimentum tissue was dissected from one individual of the worm, and high molecular weight genomic DNA was extracted using the DNeasy Blood & Tissue Kit (Qiagen) according to the manufacturer’s protocols. Sequencing a total of six paired-end or mate-pair genomic DNA libraries with insert sizes ranging from 180 bp to 7 kb were performed by The Genomic Services Lab at the Hudson Alpha Institute in Huntsville, Alabama on an Illumina HiSeq 2000 platform (see details in Table S1). Paired-end libraries (180 bp, 400 bp, 750 bp) were prepared using the 125 bp TrueSeq protocols, and mate-pair libraries (3-5 kbp, 5-7 kbp) were generated using the Illumina Nextera Mate Pair Library Kit followed by size selection. Moreover, a 10X sequencing library was constructed using the 10X Chromium protocol (10X genomics) at the Hudson Alpha Institute. The finished library was sequenced on an Illumina HiSeqX platform, using paired 151 bp reads with a single 8 bp index read.

Our workflow of genome assembly was shown in Fig. S1. The paired-end and 10X raw reads were checked using FastQC v0.11.5 (Andrews and others 2010) and quality filtered (Q score >30) using Trimmomatic v0.36 (Bolger, Lohse, and Usadel 2014). The estimation of genome size, level of heterozygosity and repeat contents of the Lamellibrachia genome was determined by analysing the kmer histograms generated from the paired-end libraries using Jellyfish v2.2.3 (Marçais and Kingsford 2011) and GenomeScope (Vurture et al. 2017) (Fig. S2). The Mate-pair reads were trimmed and sorted using NxTrim v0.3.1 (O’Connell et al. 2015) which can recognize and trim the artificial Nextera mate-pair circulation adapters. Only reads from category “mp” (true mate-pair reads) and “unkonwn” (mostly large insert size reads) were used for downstream scaffolding anlaysis. Reads from “pe” (paired-end reads) and “se” (single ends) categories were discarded.

Given that high heterozygosity of *Lamellibrachia* genome, all reads were assembled using Platanus v1.2.4 (Kajitani et al. 2014) with a kmer size of 32. Scaffolding was conducted by mapping Illumina paired-end and mate-pair reads to contigs generated by Platanus using SSPACE v3.0 (Boetzer and Pirovano 2014). Gaps in the scaffolds were then filled with GapCloser v1.12 (Luo et al. 2012). Redundant allele scaffolds were further removed using Redundans v0.13c with default settings (Pryszcz and Gabaldón 2016). Genome assembly quality was assessed using QUAST v3.1 (Gurevich et al. 2013). Completeness of obtained genome was assessed using BUSCO v3(Waterhouse et al. 2017) with Metazoa\_odb9 database (978 busco genes).

### Transcriptome assembly and analysis

Total RNA was extracted from the plume, vestimentum and trophosome tissue from the same individual of *Lamellibrachia* specimen using Trizol. RNA-Seq of adult tissues from plume, vestimentum, and trophosome was performed using Illumina HiSeq 2000 platform in Hudson Alpha. After quality checking and trimming of raw sequencing reads, transcripts were assembled de novo with Trinity. Transcript isoforms with high similarity (≥ 95%) were removed with CD-HIT-EST v4.7 (Li and Godzik 2006). Transcript abundance was estimated with Bowtie v2.2.9 (Langmead and Salzberg 2012) and RSEM v1.2.26 (Li and Dewey 2011) by mapping reads back to the transcriptomic assembly based on transcripts per million (TPM). A tissue-specifically expressed gene was defined as a gene that had over 75% of the total transcripts in a particular tissue based on TPM (Albertin et al. 2015). GO enrichment analysis was performed based on the GO annotation using PANNZER2 (Törönen, Medlar, and Holm 2018). Statistically overrepresented GO terms of trophosome-specific genes were identified using Lamellibrachia gene models as background with AgriGO (Du et al. 2010).

### Proteomics characterization.

Proteomics analyses of *Lamellibrachia* trophosome tissue were performed by Proteomics & Metabolomics facility at Colorado State University. Briefly, samples were transferred to 5mL tubes appropriate for use in the Bullet Blender Storm 5 (Next Advanced). Freshly cleaned, 3.2mm stainless steel beads were added at an approximate 1:1 sample: bead volume ratio (1-5beads). The tissue/bead mixture was then combined with 1X PBS (Hyclone) spiked with 1X Halt Protease Inhibitor cocktail (Thermo Scientific) for an approximate 2:1 liquid: solid ratio (150-600μl). Tissue homogenization was achieved using speed setting 12 for 5 minutes. The stainless steel beads were removed and 0.1mm glass beads added at approximately 1:1 sample:bead ratio. Further homogenization was achieved at speed 8 for 3 minutes. Homogenate was then transferred to 1.5mL microcentrifuge tubes and subjected to cup horn sonication (Amplitude 70, 10s pulse, 20s off, 7 minutes total exposure time; Qsonica) while suspended in ice water. Insoluble material was pelleted by brief centrifugation at 3000xg. The resulting supernatant was subjected to protein quantification by the Pierce BCA Protein Assay Kit (ThermoFisher-Pierce) following manufacturer’s instructions. Absorbance of reacted samples was measured at 550nm and protein quantification stemmed from a quadratic fit of the Bovine Serum Albumin (BSA) standard curve.

50 μg total protein was aliquoted from each sample and processed for in-solution trypsin digestion as previously described (Schauer et al. 2013). A total of 0.5μg of peptides were then purified and concentrated using an on-line enrichment column (Waters Symmetry Trap C18 100Å, 5μm, 180 μm ID x 20mm column). Subsequent chromatographic separation was performed on a reverse phase nanospray column (Waters, Peptide BEH C18; 1.7μm, 75 μm ID x 150mm column, 45°C) using a 90 minute gradient: 5%-30% buffer B over 85 minutes followed by 30%-45%B over 5 minutes (0.1% formic acid in ACN) at a flow rate of 350 nanoliters/min. Peptides were eluted directly into the mass spectrometer (Orbitrap Velos, Thermo Scientific) equipped with a Nanospray Flex ion source (Thermo Scientific) and spectra were collected over a m/z range of 400–2000, positive mode ionization, using a dynamic exclusion limit of 2 MS/MS spectra of a given m/z value for 30 s (exclusion duration of 90 s). The instrument was operated in FT mode for MS detection (resolution of 60,000) and ion trap mode for MS/MS detection with a normalized collision energy set to 35%. Compound lists of the resulting spectra were generated using Xcalibur 3.0 software (Thermo Scientific) with a S/N threshold of 1.5 and 1 scan/group.

Tandem mass spectra were extracted, charge state deconvoluted and deisotoped by ProteoWizard MsConvert (version 3.0). Spectra from all samples were searched using Mascot (Matrix Science, London, UK; version 2.6.0) against gene models of *Lamellibrachia* host and symbiont genomes (derived from (Y. Li, Liles, and Halanych 2018)) assuming the digestion enzyme trypsin. Mascot was searched with a fragment ion mass tolerance of 0.80 Da and a parent ion tolerance of 20 PPM. Oxidation of methionine and carbamidomethyl of cysteine were specified in Mascot as variable modifications. Search results from all samples were imported and combined using the probabilistic protein identification algorithms (Keller et al. 2002) implemented in the Scaffold software (version Scaffold\_4.8.4, Proteome Software Inc., Portland, OR) (Searle, Turner, and Nesvizhskii 2008). Peptide thresholds were set such that a low peptide FDR was achieved based on hits to the reverse database (Käll et al. 2007) or Protein Prophet (Nesvizhskii et al. 2003). Protein identifications were accepted if they could be established at greater than 99.0% probability and contained at least 1 identified peptide. Protein probabilities were assigned by the Protein Prophet algorithm (Nesvizhskii et al. 2003). Proteins that contained similar peptides and could not be differentiated based on MS/MS analysis alone were grouped to satisfy the principles of parsimony.

### Genome annotation.

Our genome annotation workflow was shown in Fig. S3. Gene models of *Lamellibrachia* genome were constructed following the Funannotate pipeline 1.3.0 (<https://github.com/nextgenusfs/funannotate>). Briefly, repeptitive regions in the *Lamellibrachia* genome were identified using RepeatModeler v1.0.8 (Smit and Hubley 2008) and were subsequently soft-masked using RepeatMasker v4.0.6 (Chen 2004). RNA-Seq data from different tissue were leveraged to improve the accuracy of gene prediction. RNA-Seq data were assembled *de* *novo* into transcriptomes using Trinity v2.4.0 (Haas et al. 2013) and HISAT 2.1.0 (Kim, Langmead, and Salzberg 2015) was used to algin RNA-Seq reads to the *Lamellibrachia* assembly. Tanscriptome assemblies were then passed to PASA pipeline v2.3.3 (Haas et al. 2003) to identify high-quality gene models. The aligned RNA-Seq data was used to train the *ab* *initio* gene predictions using AUGUSTUS v3.3 (Stanke et al. 2006). Protein alignments from the SwissProt database to *Lamellibrachia* assembly was generated using exonerate (Slater and Birney 2005) and Trinity/PASA transcripts were aligned to the genome using Minimap2 v2.1 (H. Li 2018). The tRNA genes were identified using tRNAscan-SE v1.3.1 (Lowe and Eddy 1997). Finally, EvidenceModeler 1.1.0 (Haas et al. 2008) was used to combine all the evidences of gene prediction from protein alignments, transcript alignments, and *ab* *initio* predictions to construct high-quality gene models. Finally, functional annotations of predicted gene models were analyzed using several curated databases. KEGG orthology was assigned using the KEGG Automatic Annotation server. Gene models were further annotated with domain structure and protein identity by InterProScan (Zdobnov and Apweiler 2001) and SwissProt database, respectively. Secreted proteins were predicted using SignalP (Petersen et al. 2011) and Phobius (Käll, Krogh, and Sonnhammer 2007) using InterProScan.

### Phylogenomics and Molecular clock analysis

Analysis of siboglinid phylogeny was conducted from publically available 16 transcriptomic data in conjunction with *Lamellibrachia* proteome (Table S2). Sequence assembly, annotation, homology evaluation, gene tree construction, parsing of genes trees to OGs, and supermatrix construction were conducted with Agalma (Dunn, Howison, and Zapata 2013). The final analyses presented here contained 13 siboglinids and four outgroups based on current understanding of annelid phylogeny. Maximum likelihood analyses were performed in IQTree under the best-fitting models for associated partition schemes determined by Modelfinder implemented in IQTree 1.6.3 (Nguyen et al. 2014) with ultrafast bootstrapping of 1000 replicates.

For molecular clock analysis, a relaxed molecular clock with a lognormal distribution and a Yule tree model was used in BEAST 2 v2.5.1 (Bouckaert et al. 2014). A calibration was placed on the node representing the most recent common ancestor (MRCA) of *Osedax* using a normal distribution with a mean of 100 MYA and a standard deviation of 10 following the findings of (Danise and Higgs 2015). Another calibration was placed on the node of MRCA of Serpulida and Sabellida using a normal distribution with a mean of 267 MYA (Sanfilippo et al. 2017). Molecular clock analyses with BEAST 2 consisted of two independent runs with 1 million MCMC generations sampled every 1000 generations. Convergence was checked and confirmed by comparing trace plots in Tracer making sure the effective sample size of each parameter was greater than 100 and that stationarity appeared to have been achieved. Log and tree files were combined using Logcombiner. A maximum clade credibility tree with mean heights was calculated using TreeAnnotater. The resulted time-calibrated tree was plotted using R package, phyloch, strap, and OutbreakTools. Bayesian inference using a molecular clock resulted in identical branching patterns as analysis with IQTree.

### Gene family analysis

After all-to-all Diamond v1.0 (Buchfink, Xie, and Huson 2014) BLASTP searches against 22 selected lophotrochozoan proteomes (Table S3), orthology groups (OGs) were identified using Orthofinder with a default inflation parameter (I=1.5). Gene ontology annotation was performed using PANTHER v13.1 (Mi et al. 2016) with the PANTHER HMM scoring tool (pantherScore2.pl). Gene family expansion and contraction was estimated using CAFÉ v2.1 (De Bie et al. 2006). For each gene family, CAFÉ generated a family-wide P value, with a significant *P* value indicating a possible gene-family expansion or contraction event. A branch-specific *P* value was also generated for each branch/node using the Viterbi method. A family-wide *P* value less than 0.01 and a branch/node Viterbi *P* value less than 0.001 was considered as a signature of gene family expansion/contraction for a specific gene family and specific species, respectively, as suggested in manual.

In addition to the above gene family expansion or contraction analysis, the protein-coding sequences were used for discovery of genes under positive selection in from *L*. *lumysi* in comparison with selected lophotrochozoan species (including *Capitella* *teleta*, *Lottia* *gigantea*, *Helobdella* *robusta*, *Octopus* *bimaculoides*, *Crassostrea* *virginica*, *Notospermus* *geniculatus* and *Phoronis* *australis*) using PosiGene, which is an automated pipeline for genome-wide detection of positively selected genes , with default settings (p < 0.05). In this positive selection analysis through the PosiGene pipeline, *L*. *lumysi* was used as the reference and anchored species for ortholog assignment of each OG.

### Manual annotation of gene families with potential interest.

In addition to the automatic annotation process mentioned above, we manually annotated genes that are general interest, such as hemoglobin gene families, genes related to amino aicd synthesize, or immunology. These genes were specifically selected *a* *priori* based on our experience after a revision of the available publications in the field. For hemoglobin genes, datasets used for HB gene family analyses, identified homologs, and their respective accession numbers are available in Fig. S# .Hbs and linker sequences of interest were obtained from “Lamellibrahcia” genome and assembled siboglinid transcriptomes (see molecular clock analysis above) via diamond blastp (evalue cutoff 1E-5) by utilizing Hb and linker sequences acquired from GenBank of siboglinids as queries (Figure #). Sequences with best hists to target proteins were annotated for protein domain architecture usig the Pfam databases included in InterProscan. After manual removal of redundant and incorrect sequences (e.g., sequences are too short or lack of globin domain), we used MAFFT 7.2.15 (Katoh and Standley 2013) to align HB amino acid sequences. Maximum likelihood analyses were performed in IQTree under the best-fitting models for associated partition schemes determined by Modelfinder implemented in IQTree with ultrafast bootstrapping of 1000 replicates.

For genes related to immunity,MIKE, I

Genes related to amino acids synthesis were from Lamellibrachia, Lamellibrachia symbionts, C. teleta were performed by using the KEGG2 KAAS genome annotation web server and then visualized by the KEGG Mapper Reconstruct Pathway too. A BLASTp search of protein sequences from genome annotation against the Swiss-Prot database was used to search for proteins that were missing in the visualized KEGG pathway.

## Results and Discussion

### Genome features

The genome of *Lamellibrachia* was sequenced using a combination of Illumina paired-end, mate-pair and 10x techniques. Results from high-throughput sequencing and genome assembly for *Lamellibrachia* are presented in Table S3 with at least 300 fold coverage using a combination of Illumina paired-end, mate-pair and 10X genomic sequencing with a variety of insert sizes. The haploid genome assembly size is ~687 Mb, similar to the result of genome size estimation using GenomeScope (~646 Mb). The N50 value of the assembled scaffolds and contigs is 373 Kb and 24 Kb, respectively. Although N50 lengths and assembly quality of *Lamellibrachia* are comparable to those of other annelids (e.g. *Capitella* *teleta*, *Hebdella* *robusta*), the overall genome completeness measured by BUSCO (~ 95%) is one of the highest among other lophotrochozoans (Table S4), indicating the completeness of the genome assembly. With the support of RNA-seq data from different tissue, we estimated *Lamellibrachia* genome contains 38,998 gene models. The genome also exhibit similar level of heterozygosity (0.6%) and repeptitive seuqences (36.92%), compared to other lophotrochzoan genomes. The repeat contents of *Lamellibrachia* genoem was shown in Table S#.

### Nutritional adaptations to a symbiotic life stage

Adult *Lamellirbachia* worms lacks of a digestive tract and rely soely on endosymbionts for nutrition. Noticebaly, only 57 genes asscociated with amino acid biosynthesis were found in the *Lamellibrachia* host genome, of which eight were identified as proteins (Fig S#). In contrast, the genome of the *Lamellibrachia* symbiont (110 genes) contains essentially complete gene sets for the biosynthesis of all 20 proteinogenic amino acids and of 11 vitamins and cofactors. The lack of 30 genes in “Lamellibrachia” compared to “Capitella” genome (90 genes) are involved in the biosynthesis of 13 out of 20 amino acids (e.g. five key enzymes in the Lysine biosynthesis pathway Fig. #). As amino acids are indispensable for protein biosynthesis in the host, the sparse presence of amino acid synthesis-related genes in *Lamellibrachia* genome may indicate that the host depends on its symbionts for supply with amino acids and cofactors. Moreover, we found a large gene expansion of nutrient uptake ABC transports in *Lamellibrachia* compared with other lophotrochozoans (Table #). These findings are consistent with previous chemichal analyses suggest that *Riftia* is also dependent on its bacterial symbiont for the biosynthesis of polyamines that are important for its metabolism and physiology (Minic and Hervé 2003). Intrestingly, a similar mechanism of host difficiency of amino acid synthesis has also been suggested in thiotrophic vesicomyid symbnioses of *Calyptogena* *magnifia* (Newton, Girguis, and Cavanaugh 2008) and vent musssel symbioses of *Bathymodiolus* *azoricus* (Ponnudurai et al. 2017). These results emphasize the host deficiency of amino acid syntheses and exchanges of metabolites between two partners mgiht to be a common strategy for chemosynthetic symbioses.

In addition to immediate release of fixed carbon and provide amino acids by the symbionts, there is evidence of a second possible nutritional mode - digestion of symbionts directly by the host, as indicated by the detection of abundant host-derived digestive enzymes in the trophosome tissue (Table S#). Although previous observations indicated that symbiont can be digested by *Riftia* (Bright, Keckeis, and Fisher 2000), the direct evidence and genetic mechanism related to symbiont digestion has not been characterized. We identified fifteen the host proteins related to lysosomal proteases that were highly expressed and dectected as proteins in the trophosome tissue, such as *Saposin* and multi copies of *Cathepsin* (Table S#). Lysosomes contain an array of digestive enzymes used for protein degradation in eukaryotic cells and are thought to play an important role in symbiont digestion of *B*. *azoricus* (Ponnudurai et al. 2017). We furthermore identified 19 major components of proteasome as proteins in the trophoseome tissue, indicating a potential role in protein degradation of symbiont digestion. Thus, our results suggest that lysosomal host proteases and proteasome may facilitate the degradation of symbiont proteins during symbiont digestion, and maintaining population size of symbionts within trophosome, or possiblly both.

Because the trosposme tissue of *Lamellibrachia* contain sulfur-oxidizing symbionts, we also identified ~ 200 bacterial proteins in the trophosome tissue to gain insights into the symbiotic relationship between the bacteria and their host. Key enzymatic genes, RubisCO and ATP citrate lyase (ACL) type II associated with these carbon fixation cycles, were identified as proteins in *Lamelibrachia* symbiotns (Table S#). Our resutls further corroborate the idea that the presence of rTCA in addition to CBB pathways for carbon fixation might be common in all vent-dwelling and seep-living vestimentiferan endosymbionts. We also identified several key components related sulfide and nitrogen metabolic pathways, and the results are largely consistent with preivous analyses.

### Hemoglobin evolution

![](data:application/pdf;base64,) **Fig 2.** Hemoglobin.

Partial alingment and gene tree of siboglinid HBs is shown in Figure #.Tthe expression of Hb subunit A1, A2, B1, B2 and linker L1-L4 were among the highest in the trophosome comared to the plume and vestimentum, and we were able to identify most of them in the mass specmetry. Consistent with previous studies (Zal et al. 1996), a single copy of A2 and B2 HB was identifed in all siboglinids with a conserved-free cystine (i.e., cysteine residues not involved in dissulfide brideges) at position 77 and 67, respectively. With the exception of A2 and B2 HB globins in *Lumbricus* *terrestris*, Cystine residues in same positions are also identified in *Cirratulus* *spectabilis*, *Sabella* *pacifica* and *Sternapsis* sp. from sulfide-free and *Arenicola* *marina* living in sulfide-rich environments (Fig. 3). These results supports the hypothesis that free cysteine residues in A2 and B2 globins have been conserved before the radiation of the Siboglinidae and potentially involve in H2S detoxification process (Bailly et al. 2002).

Surprisingly, we found a large expansion of B1 globins in *Lamellibrachia* genome with 25 copies. *Riftia* might also contain more copies since three B1 globins were identified using a set of degenerate primers by PCR in the previous study (Bailly et al. 2002). Noticablly, we found that eight copies of “Lamellibrachia” B1 seqeuences also contains a free cysteinine at position 77, same position as free cysteine in A2 globins. Five out of eight copies were highly expressed in the trophosome and one copy was identified at the protein level. Unlike A2 and B2 globins, it was long thought that B1 globins can only bind O2 and lack of the ability of sulfid binding. Although the presence of free cystine residues is not proof of sulfide binding also occurs in B1 globins, it is at least possible that the hemoglobin structure and sulfide binding function is more complex that previous thought due to unexpected large expansion and highly expression of “Lamellibrachia” B1 sequences.

Instead of free cysteinies, another hypothesis suggested that the H2S binding affinity has been mediated by the zinc moieties bound to amino acid residues at the interface between pairs of A2 chains in *Riftia* (Flores et al. 2005). Figure S# shows an alignment of amino acid sequences of A2 globins from Siboglinidae and other annelids. Amino acids involved in the binding to of zinc ions in *Riftia* A2 globin pairs are highlighted. Each A2 chain contains one complete Zn2+-binding site and shares two others with adjoining A2 subunits. The Zn2+-binding site contained within A2 chain is composed of three His residues (B12, B16, and G9) (Flores et al. 2005). However, none of these sites are conserved across siboglinids, even in vestimentiferans (Fig. S#). For example, B16 His site is replaced by a varietly of amino acids in seep-living vestimentiferans. Thus, it is less likely that the zinc sulfide binding mechanism is a conserved functional in siboglinids, and might only be a derived function only for vent-living vestimentiferans.

### Immunity function

The immune function between hosts and symbionts is a key evolutionry driver that is under strong selective pressure and has potential implications in ageing. However, the genetic machienary and funtionality of immune system in most chemosynthetic symbioses have not been extensively characterized. Our detailed analysis revealed several genes related to immunne function found duplications in *Lamellibrachia* compared with other lophotrochozoans (Table S#). Toll-like receptor (TLRs) provides vital cellular and molecular defense against invading pathogens and recognition of host-microbial symbiosis (Chu and Mazmanian 2013). Consistent with previous analysis (Luo et al. 2018), we found that TLR genes were generally expanded in most lophotrochozoans, especially in bivalves (Fig. S#). Noticebaly, we found several lineage-specific expansion of putative TLR genes in *Lamellibrachia* genome with 31 copies, whereas only five copies were found in *Capitella* genome, suggesting TLR genes in *Lamellibrachia* may play a more relevant role for symbiosis.

The initial physical encounter between tubeworms and symbionts occurs in an extracellular mucous secreted by pyriform glands by newly settled larvae (Nussbaumer, Fisher, and Bright 2006). In mucus matrices, symbionts can attach to the host using extracellular components secreted from symbionts, such as lipopolysaccharide - a major component of the outer membrane of *Riftia* symbionts. TLR4 orthologs have been hypothesized to recognize lipopolysaccharide in several studies. Although our TLR tree was not fully resolved for TLR ortholog assignemnt based on humans potentially ecdysozoan and most deuterosotmic taxa, we found a genomic expansion of TLR4-like genes in *Lamellibrachia* (7 copies) compared with *Capitella* (1 copy) from KEGG mapping. Moreover, the infection process finishes simultaneously with massive apoptosis of skin tissue during symbionts travel from host epidermal cells into trophosome (Nussbaumer, Fisher, and Bright 2006). This is consistent with that recognition of lipopolysaccharide (LPS) by TLR4 can result in indcution of sinalling cascades that lead to activation of NF-kb and the produciton ot proinflamatory cytokines (Chu and Mazmanian 2013). Intrestingly, we also found genomic expansions of Tumor necrosis factor receport (TRFR) and TNF recepotr associated factor (TNAF) (Table S#), both play key roles in NF-kb pathway. Although it is still not clear how the hosts distinguish between symbionts and pathogens in most symbioses, alkaline phosphatase has been shown to be involved in the maintenance of hemeostasis of instesting commensal bacteria in the squids, mouse and zebrafish. The commensal bactieria-dirived LPS signaling via TLR4-MYD88 leads to upreregulation of intestinal alkaline phophatase and prevents infalmmatory responses to the resident microbiota. Importantly, we also identified eight copies of alkaline phosphatase in *Lamellibrachia*, whereas only one copy was found in *Capitella*, suggesting a potential mechanism of in response to symbionts and pathogens, thus facilating colonization by the endosymbionts. Although further analysis is warranted to explicitly investigate these hypotheses,

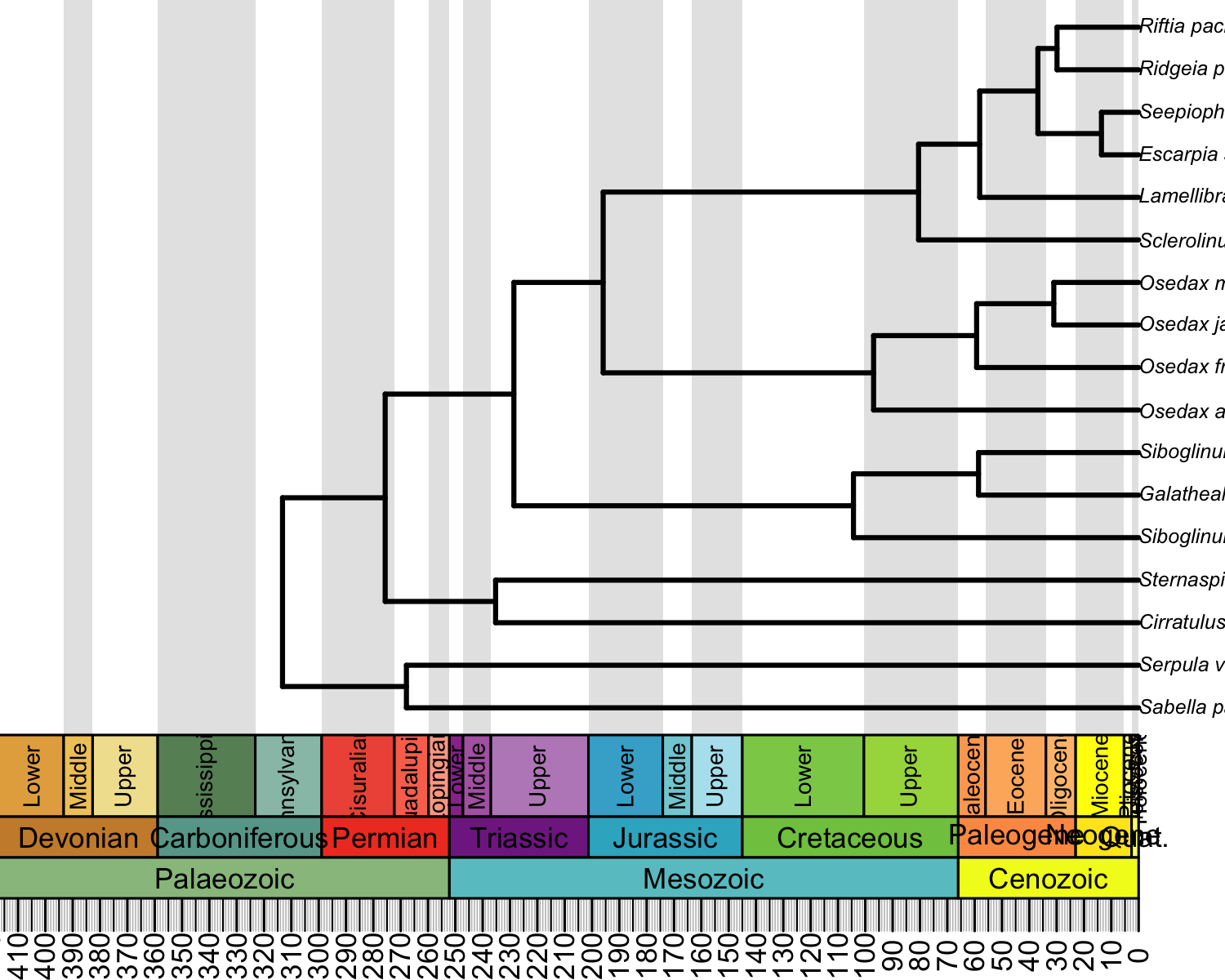
In addition of TLRs, we also found evidence of genomic expansion of NLRP family, which play a key role in the inflammasome, an innate immune system protein complex that recognizes infectious pathogens and regulates the activation of inflammatory caspases. Moreover, We found large expansions of several members of Sushi domain proteins that could be involved recognition and adhesion between hosts and symbionts.

### Aging and cell cycle

The extreme longevity of seep-living vestimentierans is expected to involve genes affecting ageing. However, genetic mechanims involved in ageing on *Lamellibrachia* are extremely scarce. Besides genomic expansions of genes related to innate immunity metioned above, our analysis highlighted several genes in *Lamellibrachia* that may play a direct role in ageing (Table #). We found evidence of positive seleciton of RNA polymerases, includes RNA polymerase I (RNAPI), RNA polymerase II (RNAPII) and RNA polymerase III subunit K (RNAPIIIK). Importantly, RNAPII can be used for recognition proteins in celluar responses to DNA damage. RNAPII can stall at a damaged DNA base may constitue the most specific signal for DNA repair, DNA damage checkpoints and apoptosis (Lindsey-Boltz and Sancar 2007) (Derheimer et al. 2007). Previous study has also suggested that RNAPII and RNAPIII might involve in DNA repair for UV damage in yeasts(Charton et al. 2015). Moreover, we identified signature of positive selection in several Histone H2 members and Lysine-specific histone demethylase 1 (Table #). Changes of histones can lead to profound chromatin structure alterations thereby influencing a multitude of biological processes ranging from transcriptional regulation to genome stability (Bönisch and Hake 2012). Changes of certain histone methyltransferases and demethylases, and alterations in histone methylation could have a huge impact on lifespan and aging phenotypes, as seen in yeast, Caenorhabiditis elegans and mammals (see review in (McCauley and Dang 2014)). These results suggest that RNA polymerases regulate the strength of DNA repair mechanisms and histone modifications or methylations may play critical role in successful ageing in *Lamellibrachia*.

We also found selection signals in microtubulin structures (tubulin alpha, beta and gamma chains), suggesting that changes in cytoskeletal dynamics may have been important in the evolution of *Lamellibrachia*. It has been shown that cell proliferation activities of the seep-living *Lamellibrachia* and vent-living *Rifita* are higher than in any other characterized invertebrates, being only comparable with tumor and wound-healing processes (Pflugfelder, Cary, and Bright 2009). Microtubules play an essential role in cell division and expresision of tubulin content increases as the cells progress toward mitosis (**???**). Intrestingly, tubulins were among the strongest selection genes in long-lived vertebrate giant tortoise genome (Quesada et al. 2018), suggesting that alterations of tubulins might be related to the increase in the number of cellular divisions associated to gigantism and high poliferation rates in *Lamellibrachia*.

### Phylogeny and molecular clock of tubeworm



Two additional *Osedax* taxa were added in the study compared to the previous siboglinid phylogenomic analyses (Li et al. 2017) (Table #). The final supermatrix dataset contains 191 genes single-copy orthologs. Bayesian inference with a relaxed molecular clock (Fig. 2) recovered the same topology as ML analysis in IQTree with strong nodal support (Fig. #). Both analyses strongly support *Osedax* is most closely related to the Vestimentifera + *Sclerolinum* clade and Frenulata is the early diverging group, as recently reported (Li et al. 2015). Within Vestimentifera, *Lamellibrachia* is sister to the remaining sampled vestimentiferans. Molecular clock analyses based on phylogenomic dataset suggest modern siboglinid diversity originated in Mesozoic (223MYA ± 80 MY), conflicting with previous hypotheses indicate a Late Mesozoic or Cenozoic approximately 50-126 MYA. The previous analyses are solely based on estimation of nucleotide divergence of COI sequences on limited taxa sampling (mainly vestimentiferans). However, mitochondrial genes of vestiemntiferans may have experienced a “slow-down” in rate of nucleotide subsitution relative to other siboglinid lineages (Li et al. 2015). Moreover, molecular clock analysis suggest a yonger split of Vestimentifernas during the Cenozoic (60 MYA). Recent analyses suggested that Jurassic tubes from Figueroa deposits is likely to have been made by vestimentiferans (Georgieva et al. 2017), but this hypothesisis is not supported in our analysis. Thus, we provide the molecular clock of the siboglinid phylogenetic tree, placing a common siboglinid ancestor as far back as the Jurassic. Siboglinid vestimentifernas might exploit and adapt to vents and seeps during Cenozoic (<65 MYA). This adds to the growing evidence that the Cenozoic was a key period for the radiation of most dominant invertebrate taxa now occupying in deep-sea chomosynthetic communities (Vrijenhoek 2013).

## Conclusion

## Ackowledgements

## Author contribution

## Supplemental Information

kable(dt) %>% kable\_styling(bootstrap\_options = c(“striped”, “hover”, “condensed”))

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