

Symbiosis, Selection, and Novelty: Freshwater Adaptation in the Unique Sponges of Lake Baikal

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Raw reads are available from the NCBI SRA under accession PRJNA431612. Assemblies, including preliminary and alternate forms, have been uploaded to Figshare, with DOI and URL 10.6084/m9.figshare.6819812 and <https://figshare.com/s/fe36239c32bbf7342756>, respectively.

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Abstract

Freshwater sponges (Spongillida) are a unique lineage of demosponges that secondarily colonized lakes and rivers and are now found ubiquitously in these ecosystems. They developed specific adaptations to freshwater systems, including the ability to survive extreme thermal ranges, long-lasting desiccation, anoxia, and resistance to a variety of pollutants. Although spongillids have colonized all freshwater systems, the family Lubomirskiidae is endemic to Lake Baikal and plays a range of key roles in this ecosystem. Our work compares the genomic content and microbiome of individuals of three species of the Lubomirskiidae, providing hypotheses for how molecular evolution has allowed them to adapt to their unique environments. We have sequenced deep (>92% of the metazoan “Benchmarking Universal Single-Copy Orthologs” [BUSCO] set) transcriptomes from three species of Lubomirskiidae and a draft genome resource for *Lubomirskia baikalensis*. We note Baikal sponges contain unicellular algal and bacterial symbionts, as well as the dinoflagellate *Gyrodinium*. We investigated molecular evolution, gene duplication, and novelty in freshwater sponges compared with marine lineages. Sixty one orthogroups have consistent evidence of positive selection. Transporters (e.g., zinc transporter-2), transcription factors (*aristaless-related homeobox*), and structural proteins (e.g., *actin-3*), alongside other genes, are under strong evolutionary pressure in freshwater, with duplication driving novelty across the Spongillida, but especially in the Lubomirskiidae. This addition to knowledge of freshwater sponge genetics provides a range of tools for understanding the molecular biology and, in the future, the ecology (e.g., colonization and migration patterns) of these key species.

Key words: Lake Baikal, sponges, Porifera, transcriptome, genome, symbiosis, freshwater.

Introduction

Freshwater sponges belong to the monophyletic order Spongillida, a unique lineage of demosponges that colonized lentic and lotic systems sometime in the Permo-Carboniferous (around 311 Ma; Schuster et al. 2018). To be able survive such a drastic change in environment, freshwater sponges adapted at the molecular, physiological, and structural level. They are able to survive a wide range of thermal conditions, including permafrost, fluctuating water levels, anoxia, and certain levels of chemicals and pollutants in the water (Manconi and Pronzato 2008). Among their physical adaptations, freshwater sponges have developed gemmules to enable them to endure winter conditions, encapsulating undifferentiated sponge cells into silica structures (Manconi and Pronzato 2008). The sponge family Lubomirskiidae (Demospongiae: Spongillida) is endemic to Lake Baikal, southern Siberia, and is a vital part of that unusual ecosystem. They colonized this lake ~3.4 Mya, ~15 My after the recent

radiation of freshwater sponges (Schuster et al. 2018). This family contains 4 genera and 13 currently accepted species (Itskovich et al. 2015). As sponges are the most prominent component of the benthic assemblage of Lake Baikal, making up around 44% of its biomass (Pile et al. 1997), they play a vital role within this ecological community.

The Lubomirskiidae possess a number of unique features. They are large for freshwater sponges, growing to around 1 m in size (Kozhov 1963). They, as with all freshwater sponges, depend on symbiotic associations with bacteria and various chlorophyll-producing microorganisms: green algae, dinoflagellates, and diatoms (Pile et al. 1997) and their diversification is yet to be fully understood. They can be described as a “species flock” (Schröder et al. 2003), and recent studies have found discrepancies between molecular and morphological data used to define species boundaries in Baikalian sponges (Itskovich et al. 2015). Among their morphological adaptations is the loss of the ability to develop gemmules (Manconi and Pronzato 2008).

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Lubomirskia baikalensis (fig. 1A) is the most abundant and best studied species of the Lubomirskiidae. It is found throughout the lake, but its morphology varies according to depth (Kozhov 1963). It grows as a mat in shallower waters, whereas in deeper areas of the lake it increases in height and begins to branch. It can form dense aggregates in favorable conditions and forms beds providing the habitat for a range of other species. Like other members of the Lubomirskiidae, *L. baikalensis* possesses symbiotic dinoflagellates assumed to be vital for proper biological function (Annenkova et al. 2011; Chernogor et al. 2013). Symbiotic bacteria also contribute to the success of this clade, as they do in other members of the Spongillidae (e.g., Latyshev et al. 1992; Gernert et al. 2005; Kaluzhnaya et al. 2011, 2012; Costa et al. 2013; Kaluzhnaya and Itskovich 2015).

Lake Baikal is the largest freshwater lake in the world by volume, the deepest and the oldest (Timoshkin 2001; Rusinek et al. 2012a). This has allowed a large number of species to adapt to its unique conditions (Timoshkin 2001; Rusinek et al. 2012b). The lake has exhibited approximately the same conditions for the past 2–4 My (Kozhova and Izmet'eva 1998), separated from other major freshwater ecosystems (Timofeyev 2010). The lake itself freezes over in winter (Kozhov 1963) but regions deeper than 250 m are a constant 3.3–4.3 °C (Shimaraev et al. 1994). Summer temperatures can reach as high as 20 °C in small bays (Pomazkina et al. 2012), although a maximum of 17 °C is more common (Kozhova and Izmet'eva 1998). Coupled with high oxygen levels throughout the water column and generally oligotrophic conditions (Kozhov 1963), these circumstances provide a challenging environment.

In the last century, the Lake Baikal ecosystem has been subject to a variety of negative environmental influences. This includes pollution from both agriculture and industry, varying water levels as a result of damming and agricultural irrigation, eutrophication as a result of fertilizer run off, and algal blooms, including those by invasive species (e.g., Romanova et al. 2015; Ciesielski et al. 2016; Kasimov et al. 2017). Sponges, with their filter-feeding lifestyle, and particularly the Lubomirskiidae, with their reliance on symbionts, may be particularly vulnerable to such pollution. Bleaching in particular has been a major issue for the Lubomirskiidae in recent decades (Kaluzhnaya and Itskovich 2015; Khanaev et al. 2018). Cases of novel diseases have also been reported (e.g., Kaluzhnaya and Itskovich 2015, 2017; Denikina et al. 2016; Kulakova et al. 2017; Itskovich et al. 2018). These changes are often associated with widespread changes to the presence and the ratio of sponge-associated bacterial communities (Kaluzhnaya and Itskovich 2015; Denikina et al. 2016; Kulakova et al. 2017). It is vital to understand the speciation patterns and diversity of the Lubomirskiidae in order to understand the impact of disease, manage conservation efforts, and ensure the survival of the Baikal ecosystem (Khanaev et al. 2018).

The biology of Baikal-endemic species has been studied from a variety of angles in the past decades (e.g., Rusinek et al. 2012b). However, only in the last few years has it been possible to study the molecular adaptations of these species,

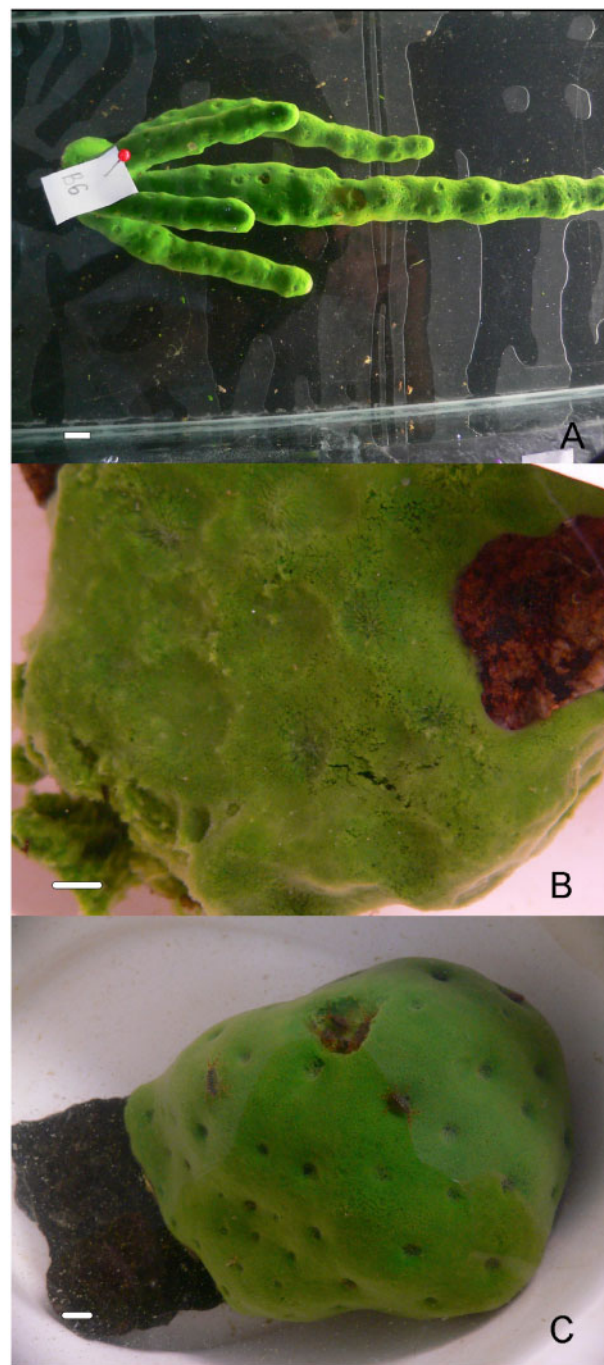


FIG. 1. Specimens used for RNA and gDNA extraction. (A) *Lubomirskia baikalensis*. (B) *Lubomirskia abietina*. (C) *Baikalospongia bacillifera*. Scale bar lengths 1 cm.

as the rise of “omic” technologies has allowed the study of even recalcitrant and rare species. The affordability of these and associated computational improvements has made such an approach attractive (Goodwin et al. 2016). This has led to the investigation of a number of Baikal species using next-generation sequencing (e.g., Rivarola-Duarte et al. 2014; Romanova et al. 2016; Naumenko et al. 2017). Such technologies have been highly successful in investigating poriferan diversity (e.g., Riesgo et al. 2014; Fernandez-Valverde et al. 2015; Kenny et al. 2018, and others). However, to date, there

have been no studies on sponges from Lake Baikal, and no freshwater sponge genomes are presently extant in the published record.

To increase our understanding of the biology of these unique sponges from a range of perspectives, we have assembled and analyzed transcriptomes of three Baikal-endemic species, *Baikalospongia bacillifera*, *Lubomirskia abietina*, and *L. baikalensis* (fig. 1). Alongside these samples, we have also assembled a draft genome for *L. baikalensis*. Our main objective was to reveal the specific molecular signatures of adaptation in freshwater sponges, and we have identified a number of key changes in genes involved in freshwater adaptation, in transcription factors, structural proteins, membrane transport molecules, and other proteins. These sequences will help us understand the biology, symbioses, population dynamics, and physiology of the idiosyncratic sponges of Lake Baikal, and freshwater sponges more generally.

Results and Discussion

Sequencing and Assembly Overview

Initial sequencing results were of variable quality and required cleaning before use in our analyses. Full details regarding this process and relevant statistics can be seen in [supplementary file 1, Supplementary Material online](#). Both clean and original reads have been uploaded to the NCBI SRA, with accession number PRJNA431612. Metrics related to the assemblies of the transcriptomes studied in this work can be seen in [supplementary file 1, Supplementary Material online, table 2](#), and that file contains further details about assembly and analysis. Individual assemblies were made using Trinity for all transcriptome data sets, each representing a single sponge. Given that we wish to consider both bacterial and metazoan sequences in the present study, it is worth considering the relative GC% of reads and our assemblies. The GC% of bacterial genomes is often, but not always, higher than that of metazoans, and higher GC% can empirically be an indicator of higher levels of bacterial sequence in a sample. This is, however, not universal. The Flavobacteriaceae, for instance, commonly found in both marine and freshwater biomes, have GC% of 31–35% (e.g., [Tekedar et al. 2017](#)).

The GC% of our paired transcriptomic reads remained stable at 49% for all samples both before and after read cleaning. This stability indicates that all samples were of comparable composition, and none contained any obvious levels of exogenous DNA or symbiotic content relative to the others. The GC% of our genomic reads declined slightly with read cleaning, from 43.5% to 41%. This finding is confirmed in our Blobplots (fig. 2), displaying assembled sequence data separated by coverage on one axis, and GC content on the other, allowing easy visualization of content. This shows that the small amount of bacterial sequences present have a very similar GC% to our assembled reads. This prohibits us from “binning” bacterial sequences by GC% to construct separate assemblies, but bacterial sequences could be recognized by BLAST similarity, as discussed elsewhere in this work.

The quantity of this bacterial sequence data (or symbiont sequences) was, however, quite small, <1/50th of the

quantity of sponge data for our transcriptomes, as can be seen most clearly in [supplementary file 3, Supplementary Material online](#), which shows the distribution of our data by superkingdom and phylum. The proportion of bases mapped to Bacteria in our genomic sequencing was higher, around 5%, and may well consist of symbiont sequences of utility to future studies, and discussed further below.

Summary statistics relating to genome assemblies can be seen in [supplementary file 1, Supplementary Material online, table 3](#). A number of assembly algorithms were assessed for their utility, with SPAdes being the best performed by several metrics. Assemblies, including preliminary and alternate forms, have been uploaded to Figshare, with DOI and URL 10.6084/m9.figshare.6819812 and <https://doi.org/10.6084/m9.figshare.6819812>; last accessed June 30, 2019 respectively.

We utilized GenomeScope to gain an understanding of the coverage of our data set, potential levels of nonsponge DNA, and to estimate the genome size of *L. baikalensis*. The results of this analysis can be seen in [supplementary file 2, Supplementary Material online](#). The inferred genome size of *L. baikalensis*, between 558 and 565 million base pairs in size, is considerably larger than that of many previously published sponge genomes ([supplementary file 1, Supplementary Material online, table 4](#)). At the same time, the mitochondrial genome of this sponge is the largest found in demosponges ([Lavrov et al. 2012](#)). The genome of *Amphimedon queenslandica* was estimated to be ~167 million base pairs in haploid size ([Srivastava et al. 2010](#)) and *Tethya wilhelma* possesses ~125 million base pairs ([Francis et al. 2017](#)). Estimates of 75 sponge species using traditional techniques ranged from 0.04 to 0.63 pg in haploid size, or ~40–630 megabases. Smaller genomes were much more common, with only 6 genomes larger than 400 megabases. Our genome is therefore definitely larger than the average sponge genome. The freshwater sponges in that latter data set, three members of the Spongillida, ranged in size from 0.31 to 0.36 pg (310–360 megabases). The size of *L. baikalensis*' genome is therefore not solely due to a freshwater environment, although this may play a part in its larger size. The unique demographic history and environment of Lake Baikal, and the unique evolutionary history of the lineage leading to *L. baikalensis*, will have played roles in the expansion of the genome of this sponge, in ways that will only be understood through examination of data sets such as the one presented here.

To estimate how much of the coding set of genes could be present in our genomic assembly, we used BlastN megablast (-evalue 0.000001 -num_threads 8 -max_target_seqs 1 -outfmt 6) to ascertain how many of the contigs present in our *L. baikalensis* transcriptome were present in the genomic assembly. 77,717 of the 81,951 contigs in the *L. baikalensis* transcriptome possessed a hit in the genome at this stringency. This strongly suggests that the transcribed cassette is well represented by the genomic assembly.

Annotation of Assemblies

To test the content of both our genomic and transcriptomic assemblies, we used the BUSCO (“Benchmarking Universal

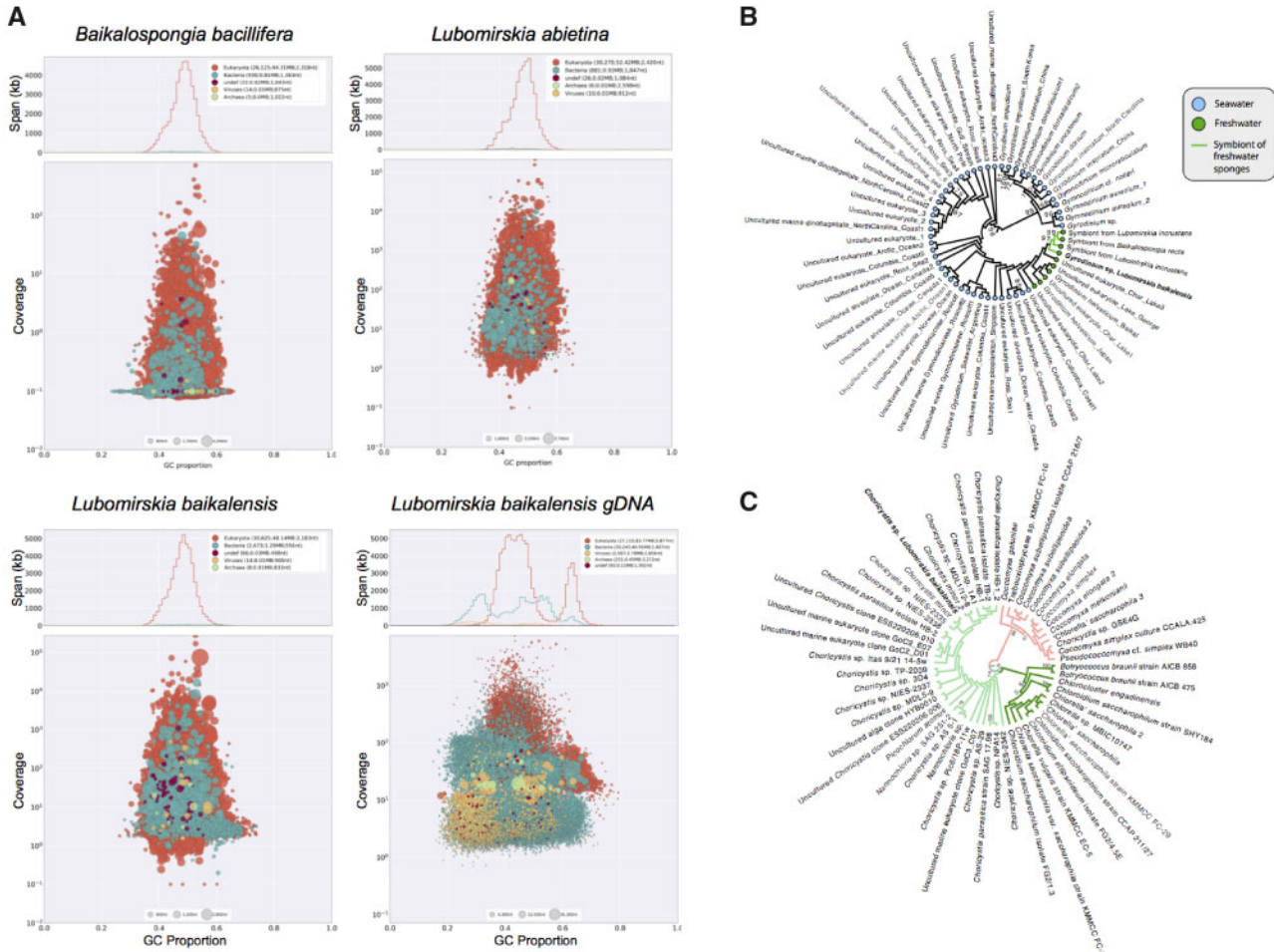


FIG. 2. (A) Blobplot results, showing distribution of annotated contigs according to GC content (x axis) and coverage (y axis) for the assemblies presented here. Summary statistics are also provided at the top of each panel. Note the bimodal distribution of GC content in the genome, which may represent differences between the coding and noncoding elements of the genome as observed in other species. (B) Maximum likelihood tree showing relationship between *Gyrodinium* sp. 18S rRNA sequence found in our *Lubomirskia baikalensis* sample and those identified previously. Note monophyletic group of freshwater samples, and internally to that clade, a monophyletic group of freshwater sponge symbiote sequences, as marked with symbols/colors noted in legend. (C) Maximum likelihood phylogeny showing relationship of *Choricystis* sp. 28S-ITS1 sequence found in our *Lubomirskia baikalensis* sample compared with previously sequenced samples from GenBank. *Choricystis* samples shown at left (light green branches) with our sample shown in bold.

Single-Copy Ortholog”) complements of highly conserved genes. In particular, we compared our data sets to the metazoan and eukaryote BUSCO complements, consisting of 978 and 303 genes, respectively. The recovery of these gene families in our data sets was almost complete (supplementary file 1, Supplementary Material online, table 5) and suggests that our transcriptomic assemblies are excellent resources for future work. Of the 303 genes in the eukaryotic BUSCO set, the maximum number of missing genes is 4 in our transcriptomic complements, and 17 in our genome assembly. Similarly, of the 978-strong metazoan BUSCO complement, the maximum number of missing genes is 46 in our transcriptomes, and 169 in our genome assembly. This compares favorably with the *A. queenslandica* genome. In the published cDNA set for *A. queenslandica*, 1.6% of the eukaryote set (5 genes) is missing, and 4.9% (49) of the metazoan complement. Our transcriptomic assemblies therefore are more complete in terms of gene recovery than that published resource, whereas

our genome is almost as complete, despite its low read coverage depth and limited library complexity. Given this level of recovery of the BUSCO set, these assemblies are therefore likely to contain the vast majority of the genetic cassette of these species, with any genes expressed at the time of sampling likely to be recovered by our assembly.

We performed automatic annotation of the transcriptomic sequences detailed here using BLAST2GO, Interproscan, and ANNEX. The complete annotations are attached to this article as supplementary file 4, Supplementary Material online. In summary, of 80,829 total contigs, *B. bacillifera* (A2) possessed 13,454 fully annotated contigs, whereas 58,890 contigs possessed no BLAST hit. For *L. abietina* (A10), 93,299 contigs included 14,623 fully annotated sequences, with 69,862 had no BLAST similarity at the given thresholds. In *L. baikalensis* (A8), these numbers were 81,877 contigs, 14,772 annotations, and 57,476 without significant similarity. The number of annotated contigs is

therefore relatively stable between all of our samples, and as can be seen in [supplementary file 5, Supplementary Material](#) online, tend to be longer than those without significant similarity, as between 75% and 80% of the assembly (by nucleotide size) is incorporated into contigs with a BLAST hit.

It is important to note that novelties, such as novel genes specific to Lake Baikal sponges, will not be well described by this annotation process, which depends on similarity in the first instance for annotation to occur. For more information on novelty, please see the last section of this article.

There is no clear signal of specific microbial sequence overrepresentation in our read data, which would be obvious at this point in the form of bacterial species with high numbers of “top hits.” However, some bacterial sequences are present, particularly that of the likely symbiont ([Wilson et al. 2014](#)) *Candidatus Entotheonella gemina*, with 88, 76, and 85 hits, respectively, for our three transcriptomes. This species is therefore likely the most commonly present bacteria in our samples, or at least the one with sequences present in GenBank for assignment. Other bacterial species are also present, although less commonly. The fuller bacterial content of our assemblies is discussed in the next section of this article.

Dinoflagellates are represented, albeit well down the list of commonly top-hit species, with *Symbiodinium microadriaticum* represented by 53, 66, and 51 sequences, respectively. It is possible that some of the sequences without blast results represent dinoflagellate sequence, as the species noted to be symbionts of Lake Baikal sponges, such as those of the genus *Gyrodinium* ([Annenkova et al. 2011](#)), are not well represented in the *nr* database.

Please note that we have not performed full gene prediction or annotation on the genome resource, as the relatively low contiguity and N50 of this resource (a consequence of low coverage and a lack of long read data) precludes most genes from occurring in their full length on a single contig. However, some information on the annotation of this resource can be derived from BLAST searches performed for Blobtools analysis, which incorporates an annotation step (see [fig. 2](#) and [supplementary file 3, Supplementary Material](#) online). For full coding gene identification, we recommend the use of our transcriptomes, while the genome will be of use for microsatellite identification, mitochondrial genomics, additional sequence determination, and other research into the wider biology of these species.

Bacterial Sequences

Our analyses revealed a small number of bacterial sequences were present in our data sets. [Supplementary file 3, Supplementary Material](#) online, shows this clearly, with a maximum of 2.4% in our transcriptomes, and 5.44% in our genomic resource. The larger proportion of bacterial content in the genomic sample (SPAdes 500 bp+ assembly) is likely the result of poly A selection procedures in our transcriptomic samples, which will preferentially target eukaryotic mRNA.

We used the results of our Blobtools annotation pathway to understand the makeup of the bacterial sequence within our SPAdes 500 bp+ genome sample. The bacterial

sequences that were present and identifiable in our *L. baikalensis* genomic sample had a relatively high abundance but low N50 when compared with eukaryote-annotated sequence, with more contigs (30,243 vs. 27,115 annotated contigs) but a much smaller N50, 1,607 bp versus 5,877 bp. This indicates to us that bacterial sequences present represent a subsample of complete bacterial diversity. It is worth noting, however, that our assemblies are made with only a single sponge specimen, which may not be representative of the population as a whole.

Our *L. baikalensis* genome resource most commonly contained proteobacterial sequences (9,880 annotated contigs, correlating to 1.9% of the reads mapped to our assembly) but also contained more than 1,000 contigs with similarity to Bacteroidetes, Verrucomicrobia, Actinobacteria, and Cyanobacteria, in order of decreasing occurrence. Less commonly, Firmicutes, *Candidatus Tectomicrobia* (with a high N50, 3,788 bp), and Spirochetes were observed in more than 100 contigs. All of these groups, with the exception of *Candidatus Tectomicrobia*, had a much lower N50 than the eukaryote (5,877 bp) and poriferan (5,088 bp) figures. This indicates that bacterial genomes were not inordinately represented in our data, and therefore were not well assembled.

Our species top-hit data revealed that *Candidatus Entotheonella gemina* was the most commonly hit individual species by BlastP identity (phylum: *Candidatus Tectomicrobia*). Our Blobtools analysis, incorporating BlastX, was able to categorize the number of contigs further. These results are available in full in [supplementary file 5, Supplementary Material](#) online. Previous studies of bacterial diversity in freshwater sponges (e.g., [Gernert et al. 2005](#); [Costa et al. 2013](#); [Gaikwad et al. 2016](#); [Seo et al. 2016](#)) have found a range of bacterial sequences within members of the Spongillidae. Often there is overlap between species (e.g., [Seo et al. 2016](#)) and in some cases freshwater sponge-specific lineages of bacteria can be found. For instance, freshwater-specific examples of Chlamydiae, Alphaproteobacteria, Actinobacteria, and Bacteroidetes species were observed in [Costa et al. \(2013\)](#).

In *B. bacillifera* (A2), Proteobacteria were the most commonly observed bacterial phylum, with 392 contigs with N50 1,275. *Candidatus Tectomicrobia* was behind, with 157 contigs of 1,145 bp N50. In order from most common to least, Bacteroidetes, Firmicutes, Actinobacteria, Cyanobacteria, and Verrucomicrobia were also present in at least double digit numbers of contig, the lattermost with an exceptionally high N50 (7,259 bp). Only nine contigs of Chlamydiae were present, but their high N50 (9,999 bp) and the obligately intracellular nature of these make them worth noting. In *L. abietina* (A10), this result was mirrored, with 407 Proteobacterial contigs (N50 1,537 bp) and 203 from *Candidatus Tectomicrobia* (1,121 bp). However, in *L. abietina*, the order of commonality in other bacterial groups is (most -> least) Actinobacteria, Firmicutes, Bacteroidetes, Cyanobacteria, Verrucomicrobia (N50 7,270), and Chloroflexi. Only 8 Chlamydiae contigs were present, but the N50 of these, 10,037, was again striking. *L. baikalensis* (A8) showed the same general trend, with one exception.

Actinobacteria is the most commonly observed clade of bacteria in this sample, with 1,589 contigs of N50 297. Proteobacterial contigs (N50 1,087 bp) and *Candidatus Tectomicrobia* sp. (191 contigs, 1,167 bp) are again well represented. Firmicutes, Bacteroidetes, Cyanobacteria, Verrucomicrobia (with a much smaller N50 than the other two samples, 976 bp), and Chlamydiae (N50 in this case only 1,618 bp) then round out the most common bacterial content in decreasing order of occurrence. Representatives of these phyla were identified previously in the *L. baikalensis* community (Kaluzhnaya et al. 2012). It would be well worth using this data for targeted resequencing of further individuals of each of our target species to determine how representative these results are of bacterial symbiote diversity in the wider population.

This indicates to us that the content of our assemblies is consistent and coherent with the literature from other freshwater sponge species (e.g., Gernert et al. 2005; Costa et al. 2013; Gaikwad et al. 2016; Seo et al. 2016). The most likely individual bacterial symbiont species within our samples is clearly related to *Candidatus Enttheonella gemina* (Phylum: *Candidatus Tectomicrobia*). It is striking that this bacterial species made the transition to freshwater to join its host, although the contemporaneity of this has not been established here. The functions provided by this species therefore remain vital, even in the markedly differing freshwater environment (Wilson et al. 2014; Liu et al. 2016) and may be necessary for the survival of the host. This symbiote can protect against heavy metals, can supply energy in anaerobic environments, and aid in CO₂ fixation (Liu et al. 2016), roles that would all be useful in freshwater in general, and Lake Baikal in particular. This is the first clear example of a sponge symbiont that is present in both marine and freshwater environments, a fact that clearly merits further investigation.

Dinoflagellate, Symbiont, and Other Sequence Content

Symbiodinium microadriaticum was represented by 53, 66, and 51 BLAST top hits, respectively, in *B. bacillifera* (A2), *L. abietina* (A10), and *L. baikalensis* (A8). Of these hits, most were represented in two or more of the three species, with seven represented in all three species. Only three (OLQ15661.1, OLP92806.1, and OLP93934.1), one (OLP92903.1), and two (OLQ11623.1 and OLP83851.1) sequences from the *nr* database were present in only one of the three species. The degree of overlap between the hits in our samples leads us to conclude that all species of sponge make use of dinoflagellate symbionts, as shown in Annenkova et al. (2011), and that the same genes are expressed at high levels in all three species. All sequences and their alignments with searched sequence are available for download in [supplementary file 5, Supplementary Material](#) online.

It is likely that these sequences do not actually represent *S. microadriaticum*—instead, they match to that species as it is the best-sequenced symbiotic dinoflagellate within the *nr* database. This is borne out by the BLAST alignments present in [supplementary file 5, Supplementary Material](#) online. In no case are hits identical to known *S. microadriaticum* sequence.

In the hit with the lowest *E* value, (to 132-kDa protein, OLP79640.1, *E* value 7.7e-130) there are 81 mismatches over a 1,058 amino acid alignment. These sequences are therefore likely from a related species of dinoflagellate, but not *S. microadriaticum* itself.

To determine which species these sequences could have been derived from, we checked for common molecular markers from dinoflagellates and compared these to genes of known orthology. We found an 18S sequence with 99.67% similarity to *Gyrodinium helveticum* in our *L. baikalensis* genomic sample, as shown in a phylogenomic context in [figure 2B](#). *Gyrodinium* is therefore further confirmed as a symbiont of Lake Baikal sponges (Annenkova et al. 2011), and our phylogeny shows a monophyletic group of freshwater *Gyrodinium* species that are the sister clade to free-living *Gyrodinium helveticum*, suggesting that they may have entered that environment contemporaneously with their hosts. They almost certainly play a role in supplying their sponge host with nutrition through photosynthesis, and may supply specific metabolites to their host (Müller et al. 2009). All accession numbers and alignments used in making this phylogeny can be found in [supplementary file 5, Supplementary Material](#) online.

We were also able to use our Blobplot results to examine the contents of our genomic resource. A total of 104 contigs, with an N50 length of 2,651 bp, were identified as belonging to the Bacillariophyta by blast similarity. This is not a high number, and indicates that the symbionts are not present in high numbers within our samples, at least at the time of sampling.

Many of the best assembled sequences present in our genomic data derive from unicellular algae, which are common symbionts of freshwater sponges (Feranchuk et al. 2018). In our genomic sample, the Chlorophyta are the second most commonly hit phylum after Porifera, with 1,359 very well-assembled contigs of N50 21,412 bp—an N50 fourfold higher than that for our sponge data. In our transcriptomes, 189 *L. baikalensis* (A8) hits are seen, but only 14 and 21 contigs in *L. abietina* (A10) and *B. bacillifera* (A2), respectively. As our genomic and transcriptomic sample for *L. baikalensis* are derived from the same tissue, we suspect that a member of the Chlorophyta was particularly abundant in that specimen, and could have been performing a symbiotic role, as has been reported previously in freshwater sponges (Sand-Jensen and Pedersen 1994; Feranchuk et al. 2018). They play clear roles in providing sustenance through photosynthesis, which greatly benefits the sponge host (Chernogor et al. 2013). Phylogenetic analysis of the 18S-ITS1 sequence of this symbiont from our genomic sample ([fig. 2C](#)) identifies it as *Choricystis* sp., placed as sister to a free-living *Choricystis minor* collected from a lake in Germany (Krienitz et al. 1996). These algae are known symbionts of freshwater sponges, and this record confirms their role in Lake Baikal sponges. The accession numbers and alignments of sequences used for this phylogeny are available in [supplementary file 5, Supplementary Material](#) online.

We also note, as mentioned in the bacterial section above, bacterial species with similarity to *Enttheonella* (Wilson et al. 2014) are also present. These findings, alongside those

published previously, suggest the microbial symbiota of the sponges of Lake Baikal is diverse and species dependent. As noted above, resequencing multiple individuals from a range of seasons, using the data presented here to aid primer design, would allow more complete understanding of the full contribution of symbionts to the survival of these species.

Mitochondrial Genomes, and Mitochondrial and Nuclear-Derived Phylogenies

The mitochondrial genomes of several Lake Baikal sponges have been published previously (Lavrov 2010; Lavrov et al. 2012; Maikova et al. 2016). They display a number of special characteristics, notably the proliferation of small “hairpin” inverted repeats, which act as a source of variation. To confirm the identity of the sponges sequenced here, and to identify regions of difference at the DNA and coding level, we studied the sequence of the mitochondrial genomes of the three species investigated, and compared them to previously published work. Of the three species included in this article, only *L. abietina* has not been sequenced previously. *Lubomirskia abietina* sequences have been uploaded to GenBank with accession numbers MH697685–MH697697.

Of the sequences presented here, the mitochondrial sequence of *L. baikalensis* derived from sample A8 seems closely related to that of the previously sequenced example of this species, whereas *B. bacillifera* differs somewhat from the example in GenBank, which appears more similar to *B. intermedia*. The small number of changes between these sequences, however, may render the differences inconsequential compared with morphological evidence (as suggested by low posterior probability of a real clade occurring between these sequences, which could be collapsed to a polytomy), and indels also add data, as discussed below. The phylogeny shown in figure 3 seems to indicate paraphyly in both *Lubomirskia* and *Baikalospongia*, albeit in some cases with limited posterior probability support. This mirrors the phylogeny previously observed in Lavrov et al. (2012) (fig. 6 of that article), adding extra taxa to the outline presented there. *Swartschewskia papyracea* and *Rezinkovia echinata* seem to render the *Lubomirskia* paraphyletic, whereas the *Baikalospongia* seem to be paraphyletic as a mixed paraphyletic sister group of this clade. From the evidence presented in this figure, taxonomic revision of these clades appears warranted.

The phylogeny shown in figure 3, and particularly the branch lengths, does not fully show the level of divergence of the Lake Baikal clade, as gaps and indel regions have been excluded for the purpose of phylogenetic analysis. Several of these sites show clear diagnostic differences between the sponges of Lake Baikal and other freshwater species. One of these regions, that of *nad1*, can be seen in figure 3B, by way of example. This alignment clearly shows the disparity between freshwater sponges of Lake Baikal and those from further afield, but also (in position 826) shows how a diagnostic difference separates *L. baikalensis* and *Rezinkovia echinata* from the other species examined here. A fuller examination of the poriferan diversity of Lake Baikal, considering both morphological and genetic evidence, is therefore likely warranted to

resolve these species into a taxonomically and systematically cohesive framework.

As part of the process of studying the signatures of selection within freshwater sponges, the Phylotreepruner output alignments of all 3,222 genes to be tested were concatenated, and used to construct a robust phylogeny for our species, spanning 3,242,264 amino acid residues although all gaps and indels were removed for phylogenetic inference. This phylogeny (and our tests of signatures of selection) included the three species of Lake Baikal examined here, alongside three other members of the Spongillida (*Spongilla lacustris*, *Eunapius fragilis*, and *Ephydatia muelleri*). Five marine outgroup species (*Mycale phyllophilla*, *Haliclona tubifera*, *Petrosia ficiformis*, *A. queenslandica*, and *Ircinia fasciculata*) were chosen for their taxonomic position and sequenced gene complements.

Phylogenetic inference was performed by MrBayes using a by-gene partitioned GTR analysis, and the resulting phylogeny can be seen in figure 4A. In this phylogeny, the freshwater sponges form a distinct clade corresponding to the order Spongillida (Manconi and Pronzato 2002), with maximal posterior probability support. *Mycale phyllophilla* is noted as the outgroup to this clade, suggesting poecilosclerids are more closely related to Spongillida than the other species represented here, albeit with weak (0.72) posterior probability. The three species of haplosclerid examined form a monophyletic group with posterior probability of 1, and the sole member of the Dictyoceratida (and Keratosa) present in our sample, *I. fasciculata*, is used to root the tree shown here. This is in agreement with the view of interrelationships put forward in Morrow and Cárdenas (2015) (see fig. 2 of that work).

Within the Spongillida, *Lubomirskia* forms a monophyletic grouping, with *Baikalospongia* as the sister clade. This is in contrast to the mitochondrial tree, and likely represents the increased depth of data available to distinguish these clades. *Ephydatia muelleri* is strongly supported as the outgroup to the *Lubomirskidae*, with *E. fragilis* and *Spongilla lacustris* placed in a monophyletic group as sister to the (*Lubomirskidae* + *Ep. muelleri*) clade. This mirrors the results of prior, individual and several gene/ITS based phylogenetic studies in freshwater sponges (e.g., Meixner et al. 2007; Erpenbeck et al. 2011). As such, the monophyly of freshwater sponges, and the hypothesis of the independent evolution of endemic sponge species locally, from cosmopolitan founder species, seems secure (Meixner et al. 2007).

Signatures of Molecular Adaptation to Freshwater Conditions

To discern how freshwater sponge species have evolved to cope with their environments, we have utilized the HyPhy and PAML software suites to identify genes where there are marked signals of selection in freshwater sponges when compared with the ancestral condition. The phylogeny of sponges used to conduct these tests, the concatenated nuclear gene phylogeny, can be seen in figure 4A, and is discussed further above. In total, 3,222 single-copy orthologous alignments remaining after pruning paralogous sequences with Phylotreepruner, henceforth referred to as “orthogroups,”

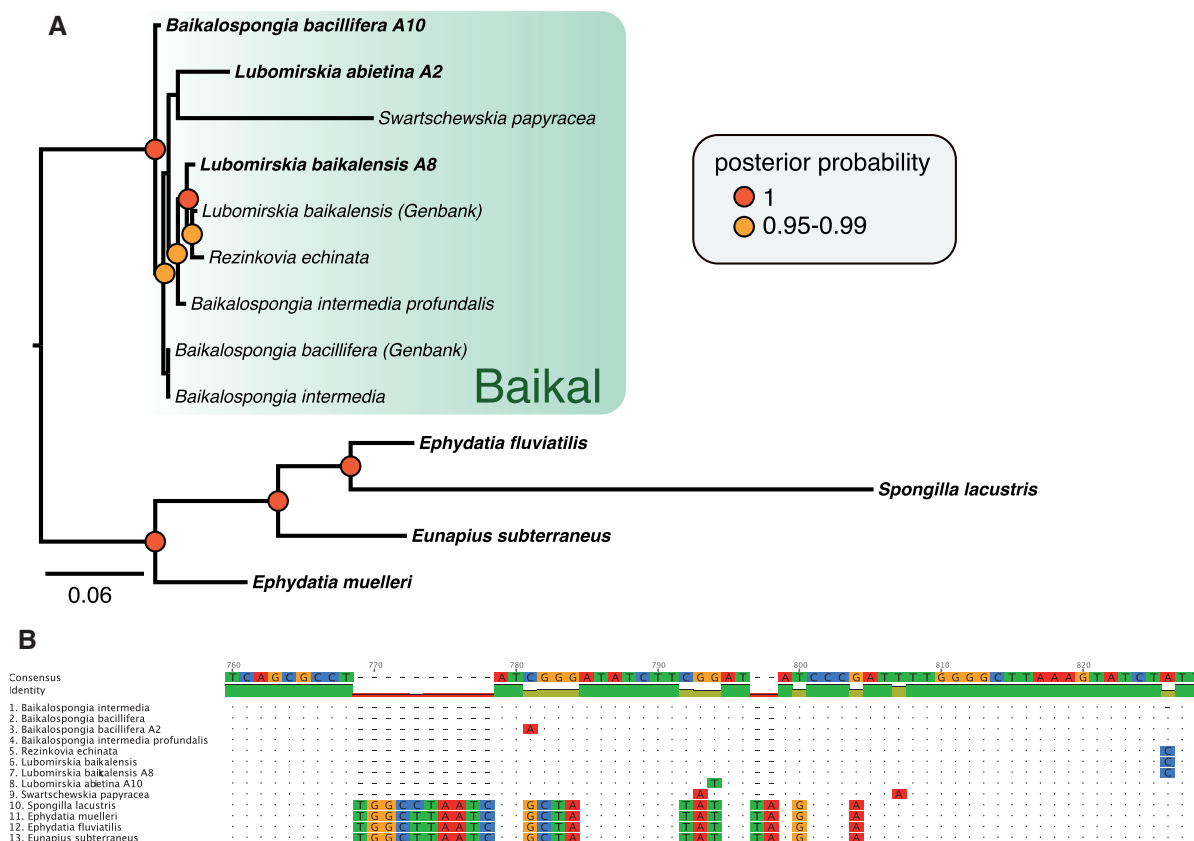


FIG. 3. (A) Phylogenetic relationships of a variety of freshwater sponge species, inferred using Bayesian methods, based on alignment of nucleotide sequence from mitochondrial protein coding and rRNA genes. Numbers at bases of nodes indicate posterior probability, number at base of tree (under scale bar) indicates number of changes per site at unit length. (B) example of indels not used in tree, but nonetheless present in alignment. These indels (example from *Nad1* provided) provide further data that can be used to support clades, but are not represented in the phylogeny shown (as any site without sequence data is excluded from that analysis). Sponges endemic to Lake Baikal are, on the basis of this evidence, firmly supported as a monophyletic clade, to the exclusion of other freshwater sponges.

were tested from the 11 transcriptomes we used in this experiment.

We used the concilience of several tests to validate our findings, to avoid artifactual or spurious results. In particular, we used CodeML, Busted and aBSREL to test for signatures of selection using a combination of approaches (branch-site model, alignment-wide episodic diversifying selection, and adaptive branch-site random effects likelihood, respectively). These methods use slightly varying means to detect selection, so a combinatorial approach is most suitable for ensuring that identified selective events are well supported by evidence, rather than the product of branch-specific signals or errors that could yield false positives (Venkat et al. 2018).

A total of 277, 324, and 252 orthogroups were identified as bearing signatures of selection by CodeML, Busted, and aBSREL, respectively. These represent 566 unique orthogroups, with 287 of them overlapping in some way, as can be seen in figure 4B. The fact that 566 orthogroups, 17.6% of those tested, show some sign of selection is suggestive of broad scale changes in sequence as a consequence of adaptation to a freshwater lifestyle. Of these, 61 orthogroups were identified by all 3 of our tests (see fig. 4B), and it was these that we concentrated on in further analyses. These orthogroups,

which can be seen listed in table 1, with full details given in supplementary file 5, Supplementary Material online, represent a variety of gene families. Of these 61 sequences, only one was unannotatable by BLAST identity to previously described genes. Annotation was aided by the inclusion of the most recent *A. queenslandica* resource in our test data set, and the sole unannotatable orthogroup represents a newly identified sequence (in the recent *A. queenslandica* transcriptome) not originally annotated in the *A. queenslandica* genome, which nonetheless is present in all of the sponge species studied in this test. It does not have any matches on the NR or PFAM-A databases, with an *E* value cutoff of 1. It contains an ORF 175 amino acids in length and is thus likely to be a bona fide protein coding gene.

The 61 orthogroups highlighted by this analysis correspond to transcription factors, structural proteins, membrane transport molecules, and a variety of other gene families (table 1). This diversity reflects the wholesale nature of changes required by adaptation to a novel freshwater environment. To highlight some genes in particular, transporter genes such as *zinc transporter 2* (OG0000120) and *importin subunit alpha-6* (OG0001194), transcription factors such as *aristaless-related homeobox* (OG0006570), and structural peptides such as *actin 3* (OG0000142) are all

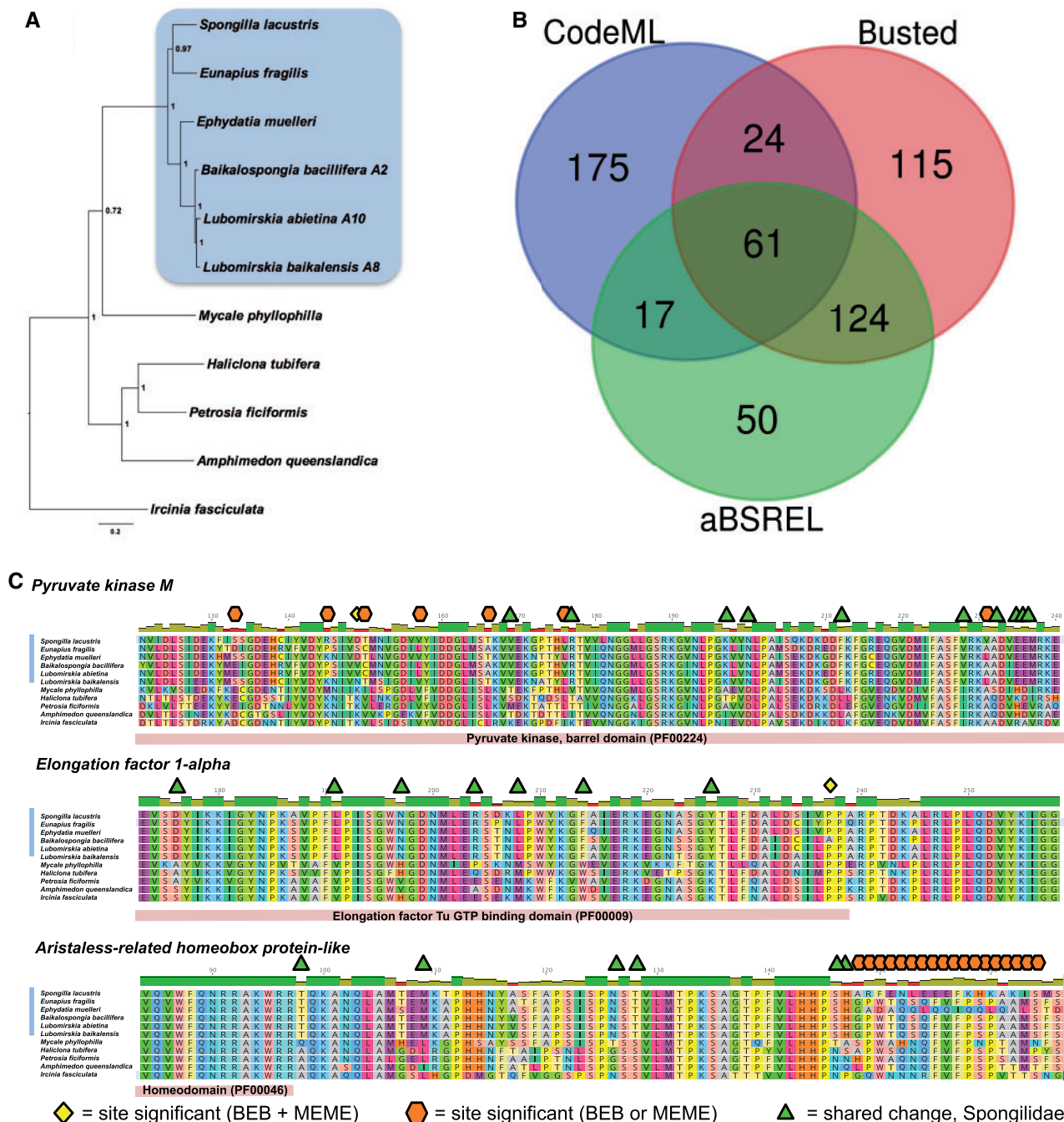


Fig. 4. (A) Phylogenetic relationship of freshwater sponge species and outgroup taxa, inferred from a concatenated multiple gene alignment using partitioned GTR analysis in MrBayes (3,222 genes, 3,242,264 site alignment, before trimming). This tree was used as the basis for tests of selection on the freshwater lineage, the results of which are summarized in (B) orthogroups displaying significant results for tests of selection under several tests, shown in a Venn diagram indicating consilience of results. (C) Examples of genes and sites under selection, with sites marked according to key at bottom of figure. Domain locations are indicated below each gene as appropriate. Note that further site-level (MEME and BEB) results are available in [supplementary file 5, Supplementary Material](#) online.

implicated. However, despite this diversity, some genes have clear roles in homeostasis and membrane transport that would be under particular pressure as a result of the adaptation to a freshwater environment. Several of the genes identified by our analysis are transmembrane or membrane-associated proteins, such as the aforementioned transporters, *integrin alpha-9* (OG0001031), *neurobeachin* (OG0000141), *UNC93-like protein* (OG0005914), and *tweety*

homolog 2 (OG0005907). Several are also involved in the Rho GTPase pathway, including *vav-1* (OG0000757), *rho* GTPase-activating protein 39 (OG0001117), and *rho* GTPase-activating protein 2 (OG0002195). Given the widespread roles of Rho GTPases in maintaining homeostasis and cellular functionality (Bustelo et al. 2007), their modification to a freshwater environment under selective pressure would be necessary.

Table 1. Orthogroups (OG) with Consilient Signals of Molecular Evolution.

Alignment Number	GenBank Hit	Mapped to GO Term(s)	Alignment Number	GenBank Hit	Mapped to GO Term(s)
OG0000044	Fibrinogen C domain-containing protein 1-A-like	No	OG0001408	Uncharacterized protein LOC109593314	Yes
OG0000120	Zinc transporter 2-like	Yes	OG0001488	UPF0600 protein C5orf51 homolog	No
OG0000141	Neurobeachin-like	No	OG0001657	Protein ADP-ribosylarginine hydrolase-like	No
OG0000142	Actin-3-like	No	OG0001662	Elongation factor 1-alpha	Yes
OG0000150	Proteinase T-like	Yes	OG0001704	Apoptosis-inducing factor 3-like	No
OG0000161	Autophagy-related protein 16-1-like	No	OG0001826	WD and tetratricopeptide repeats protein 1-like isoform X1	No
OG0000227	Uncharacterized protein LOC109592610 isoform X2	No	OG0002175	Tyrosine-protein phosphatase nonreceptor type 11 isoform X2	No
OG0000236	Protein F37C4.5-like	No	OG0002186	U3 small nucleolar ribonucleoprotein protein MPP10-like	Yes
OG0000300	Dual oxidase 1-like	Yes	OG0002195	Rho GTPase-activating protein 26-like isoform X2	Yes
OG0000375	SEC14-like protein 2	Yes	OG0002335	SH3 domain-containing kinase-binding protein 1-like isoform X2	Yes
OG0000378	Glutamyl aminopeptidase-like isoform X2	Yes	OG0002484	Radixin-like	Yes
OG0000422	Annexin-B12-like, partial	No	OG0002622	Tetratricopeptide repeat protein 14	No
OG0000434	long-chain-fatty-acid-CoA ligase ACSBG2-like	No	OG0002646	Alpha-xylosidase-like	Yes
OG0000519	Gamma-glutamyltranspeptidase 1-like	Yes	OG0002712	Uncharacterized protein LOC109586818	No
OG0000528	DnaJ homolog subfamily A member 3, mitochondrial-like isoform X1	Yes	OG0002718	Pyruvate kinase PKM-like	Yes
OG0000631	Cytochrome b-245 heavy chain-like	Yes	OG0002786	Heparan-alpha-glucosaminide N-acetyltransferase-like isoform X2	No
OG0000658	Disintegrin and metalloproteinase domain-containing protein 17	Yes	OG0003043	Uncharacterized protein LOC100635535	No
OG0000696	2'-5'-Oligoadenylate synthase-like protein 2	Yes	OG0003137	Uncharacterized protein LOC105316736 isoform X2	Yes
OG0000757	Protein vav-1-like	Yes	OG0003269	Acyl Co-a binding	No
OG0000774	TGF-beta-activated kinase 1 and MAP3K7-binding protein 1-like	Yes	OG0003737	Tetratricopeptide repeat protein 1-like isoform X1	No
OG0000885	Tyrosine-protein kinase Tec-like	Yes	OG0003883	Flowering time control protein FY-like	No
OG0000894	Poly(rC)-binding protein 2-like	No	OG0004236	Dual oxidase maturation factor 1-like	Yes
OG0000984	Ataxin-7-like protein 3	No	OG0004507	Stromal membrane-associated protein 1-like	Yes
OG0001031	Integrin alpha-9-like	Yes	OG0004509	Brefeldin A-inhibited guanine nucleotide-exchange protein 1	Yes
OG0001052	Glucosidase 2 subunit beta-like, partial	Yes	OG0005056	Homocysteine-responsive endoplasmic reticulum-resident ubiquitin-like	Yes
OG0001078	Protein DD3-3-like	No	OG0005907	Protein tweety homolog 2-like	Yes
OG0001082	Guanine nucleotide-binding protein G(q) subunit alpha-like	Yes	OG0005914	UNC93-like protein MFSD11	Yes
OG0001093	Probable ATP-dependent RNA helicase DDX49, partial	Yes	OG0006570	Aristaless-related homeobox protein-like	Yes
OG0001117	Rho GTPase-activating protein 39-like isoform X1	Yes	OG0007030	28-kDa heat- and acid-stable phosphoprotein-like	No
OG0001194	Importin subunit alpha-6-like	Yes	OG0007208	Pre-mRNA-processing factor 40 homolog B-like	No
OG0001217	No BLAST/PFAM Annotation	No			

NOTE.—Thirty-five of these could be mapped to Gene Ontology (GO) terms, as described in text. Full details of sites and significance, along with mapped GO terms, can be found in [supplementary file 5, Supplementary Material](#) online.

We investigated the nature of the precise changes, and the exact sites under selection pressure, in these sequences by performing tests in Mixed Effects Model of Evolution (MEME, [Murrell et al. 2012, 2015](#)), as well as by investigating the Bayes

Empirical Bayes (BEB, [Yang et al. 2005](#)) results from CodeML analysis. Of the 61 orthogroups identified as significant by all 3 tests described above, all but one possessed at least one amino acid site noted as under significant evolutionary

pressure by either our BEB or MEME test. The sole exception, OG0002186, is annotated to be *U3 small nucleolar ribonucleoprotein protein MPP10-like*. These results are also listed in [supplementary file 5, Supplementary Material](#) online, although please note that site number refers to that position in the alignment, and not an individual amino acid (as this will vary from species to species). This extra, almost perfect, support from site-based tests gives us even more confidence in the veracity of these results, and the strength of the selection pressures brought to bear on these genes.

In [figure 4C](#), we show some examples of the sites that are flagged by MEME and BEB as under selection. Three disparate genes are shown, *Pyruvate kinase M*, *Elongation factor 1-alpha*, and *Aristaless-related homeobox protein*. These were chosen for their interesting patterns of selection under BEB and MEME analysis, as well as their diverse functional utility. *Pyruvate kinase M* catalyzes glycolysis, allowing energy production even in anoxic environments ([Gupta and Bamezai 2010](#)). In this gene, there are a raft of changes identified by either BEB or MEME as significant proof of positive selection, but in only one case (site 149) do these tests agree. However, these sites do cluster in close proximity. In *Elongation factor 1-alpha* ([Sasikumar et al. 2012](#)), which aids in delivery of tRNA to the ribosome, there are numerous freshwater sponge-specific changes, which are shared across the monophyletic Spongilidae. However, these are not necessarily detected as significant changes by BEB and MEME analysis. Instead, a change from proline (with its large cyclic sidechain) to alanine (with its small aliphatic sidechain) in *B. bacillifera* is noted by both tests as the most significant change to have occurred in the sequence of this gene.

The last example, *Aristaless-related homeobox protein*, a member of the PRD class of homeobox-containing genes, has a cluster of sites identified as positively selected, lying together toward the C terminus of the protein from the homeodomain. These sites are detected by MEME and BEB, but again, instead of agreeing on the same sites, only one of these two tests flags positive selection at any individual site, in an interleaving fashion. The exception to this is only at site 173, where they agree. It is clear from the alignment shown in [figure 4C](#) that this region of the protein is more prone to change than the remainder of the protein sequence. This conservation is especially clear in the indicated homeodomain region. The potential for positive selection in the variable region is clear, although the role of this section of the protein is at present unknown.

We examined our BEB results to see whether some amino acids were more likely to be the site of selection than others. Of the 424 sites identified by BEB across the 61 orthogroups, the most likely amino acid to exhibit positive selection is lysine (K), which occurs 38 times. Serine (S) occurred 33, leucine (L) 29, and aspartic acid (D) and alanine (A) occurred 28 times. These amino acids contain a variety of charged, polar, and hydrophobic side chains, and thus these changes are likely to reflect a variety of changes within these molecules. In contrast, tryptophan (W) was the least likely to be positively selected, occurring only four times, likely a result of the large side chain which would prove difficult to

incorporate into protein structures. Cysteine (C), 7, and phenylalanine (F) and tyrosine (Y), with only 10 occurrences, were similarly less likely to be subject to positive selection, likely as a result of their tendency to form cross links and large side chains, respectively.

The large number of changes and the diversity of the genes affected reflect the profound changes which must have occurred across the genome of freshwater sponges in order to adapt to the markedly different osmotic, climatic and environmental differences posed by freshwater environments. As all freshwater sponge species examined here are descended from the same common ancestor, we are unable to use convergent signal to verify that these signals of selection are the result of freshwater-specific cues. They could therefore derive from other selection pressures within this clade in the time since their stem lineage diverged from their sister taxa. However, as these freshwater sponges share these signatures of positive selection, they are likely to be necessary for their survival to the present day. Functional testing of these proteins and their performance in freshwater when compared with their ancestral forms would allow the precise nature of the conformational and functional changes in these proteins to be determined, but is beyond the scope of this article.

Previous “omic” studies looking into adaptation to freshwater environments have tended to focus on metazoans with complex body plans, for example, fish ([Mäkinen et al. 2008](#)) and prawns ([Rahi et al. 2017](#)). The molecular adaptations of these species to less saline environments have often been found to be focused on genes expressed in gills and kidneys, as these are the organs most involved in maintaining homeostasis under the contrasting osmotic pressure found there. Sponges must utilize such adaptations across the entirety of their bodies, without the benefit of impermeable membranes, shells, or skins. It is unsurprising that sponges exhibit profound changes across the majority of their molecular repertoires as a result of the pressures of freshwater environments. As sponges only populated freshwater on a single occasion, despite being widespread in marine environments, this transition cannot have been straightforward. Studies such as those described here will allow us to understand the myriad demands of this process, and contrast them with those encountered by independent transition events to the same environment.

Overrepresentation of Gene Families or Categories

To gain deeper understanding of the links between the seemingly disparate genes with evidence for selection, contrasted with those genes without such evidence in freshwater conditions, we used the established system of gene ontology (GO) categories. This allowed us to investigate the links between our gene lists by determining how they are linked by shared molecular functions and pathways. GO categories overrepresented in the 61 positively selected genes seen in [table 1](#) were annotated for all three subontologies (biological process [BP], cellular component [CC], and molecular function [MF]) within the GO schema, and the significantly overrepresented GO terms can be seen in [figure 5A](#). Thirty five of the 61 genes were able to be mapped to GO terms ([table 1](#)),

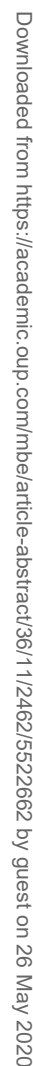


Figure 5B shows these enriched GO terms represented as networks for the CC and BP subontologies (MF categories did

not overlap meaningfully and are not shown). These networks show that the enriched GO terms within our genes, for all their apparent disparity when viewed as a list, overlap considerably in componentry and biological process. Within total “GO space,” enriched GO terms are tightly clustered for both CC (upper) and BP (lower) networks. Links can be seen between the disparate GO terms listed in [figure 5A](#), with only 2 (CC) and 3 (BP) separate clusters in our data set.

GO analysis therefore suggests that within our gene list ([table 1](#)) there is coherent, linked GO signal, and the list, while containing genes seemingly unrelated at first sight, is linked by underlying processes. Freshwater sponges will, at the cellular level, be under similar evolutionary pressures to other organisms who have made the move to this environment. It is therefore both expected and confirmation of the validity of our analyses that genes and mechanisms involved in membrane function, transport and related processes, which would be intimately affected by changes in osmotic pressure and environment, appear in our GO terms and networks.

Novelty in Freshwater Sponge Gene Complements

We assayed for novel genes and gene family expansions to discern whether there was any systematic change in the occurrence of novelties in freshwater sponges. The results of these investigations can be seen in [figure 6](#), as inferred by Orthofinder 2, which infers orthogroups using a combined reciprocal search (DIAMOND), clustering and phylogenetic approach, through generation and interpretation of gene trees. These orthogroups do not always correspond to individual genes, due to effects such as paralogy, but consist of “all sequences descending from a single gene in the last common ancestor of all the species being considered” ([Emms and Kelly 2015](#)).

We mapped the occurrence of duplications within orthogroups within our data set and displayed them on a species tree (made from our data, concatenated and partitioned) in [figure 6A](#). As can be seen from this data, duplication is particularly common at node N10, leading to Lake Baikal sponges. 7,313 duplications are noted here, and a further 1,829 in the node leading to the genus *Lubomirskia*. Generally, high levels of duplication are seen throughout the freshwater sponge clade when compared with marine outgroups. This is not due to the use of transcriptomes rather than genomic sequence, as transcriptome data are also used for four of the seven marine species and do not show this trend. Only at N1, the base of the Heteroscleromorpha (*sensu* [Cárdenas et al. 2012](#)) are similarly high levels of duplication found (4,269 duplications). A moderate signal for duplication is also seen at N3, at the base of the Haplosclerida (1,646 duplications), but this not comparable to the large degree of duplication seen in the Spongillidae (e.g., 3,642 duplications at N5, at the base of the Spongillidae). Of the 61 genes found to be under positive selection, every single one of them has been duplicated in at least one lineage of freshwater sponge. These genes are therefore evolving in multiple ways to allow these sponges to survive in freshwater conditions, adding further support to their status as key components of this transition.

The large number of duplications across freshwater sponge phylogeny is surprising, as their close relationships would suggest that they would contain more shared gene duplications, whereas outgroups would have more gene duplications, accrued over evolutionary time. This is particularly true in the case of Lake Baikal sponges, which are closely related and diverged from one another relatively recently. This finding is not a consequence of undersampling of genetic resources in our marine outgroups, as three genomes (*A. queenslandica*, *Xestospongia testudinaria*, and *Tethya wilhelma*) were used as comparison points. We hypothesize therefore that freshwater sponges are adjusting to their environment by large-scale duplication of their genes, as well as by changing their sequence under evolutionary pressure as noted earlier. These additional duplicates will provide raw material for evolution in a variety of ways, allowing subfunctionalization, regulatory changes, and the emergence of novel functions from ancient genes.

To check whether species-specific novelties (sequences not observed in, or assigned to orthogroups shared with, other species), also exhibited this trend, we calculated their abundance as can be seen in [figure 6B](#). In contrast with our gene duplication results, freshwater sponges exhibited few novel genes when compared with outgroup taxa. Similarly, [figure 6C](#) shows species-unique orthogroups, where more than one sequence exists for a gene, but only in a single species. This shows a similar distribution, with species-specific orthogroups more common in our marine outgroups. These findings will be biased somewhat by the close relationship between freshwater taxa, making it more likely that novelties are shared by these species. However, it is important to note that freshwater taxa, and particularly Lake Baikal sponges, do not exhibit large amounts of novelty on an individual species level.

It is difficult to assign identity or function to these genes, as they are novelties to the individual lineages or clades in which they are found. In the case the novelties noted within the Spongillidae by Orthofinder, they have no shared ortholog within any of the marine outgroups shown in [figure 6A](#), including three genomic resources, which should be reasonably complete data sets. The genes recorded here are therefore highly likely to be true novelties. They may, however, belong to larger gene families, or possess some sequence signatures which give clues as to their identity. It will be particularly interesting to compare these novelties to those found in freshwater-adapted species from other phyla, when such data become available.

To examine the extent to which orthologs and orthogroups are shared between the species examined here, we plotted this data on a matrix ([fig. 6D](#)) and used color shading to display it as a heat map. It is clear from this data that in general freshwater sponges share more sequences in common than the other outgroup species in our data set do with one another. Only *M. phyllophilla* and *T. wilhelma* are similar to the same extent, and *M. phyllophilla* also seems to share a conserved gene set with most of the other sponges in our sampling. In contrast, *Haliclona tubifera*, *A. queenslandica*, and *X. testudinaria* are the species with the most divergent

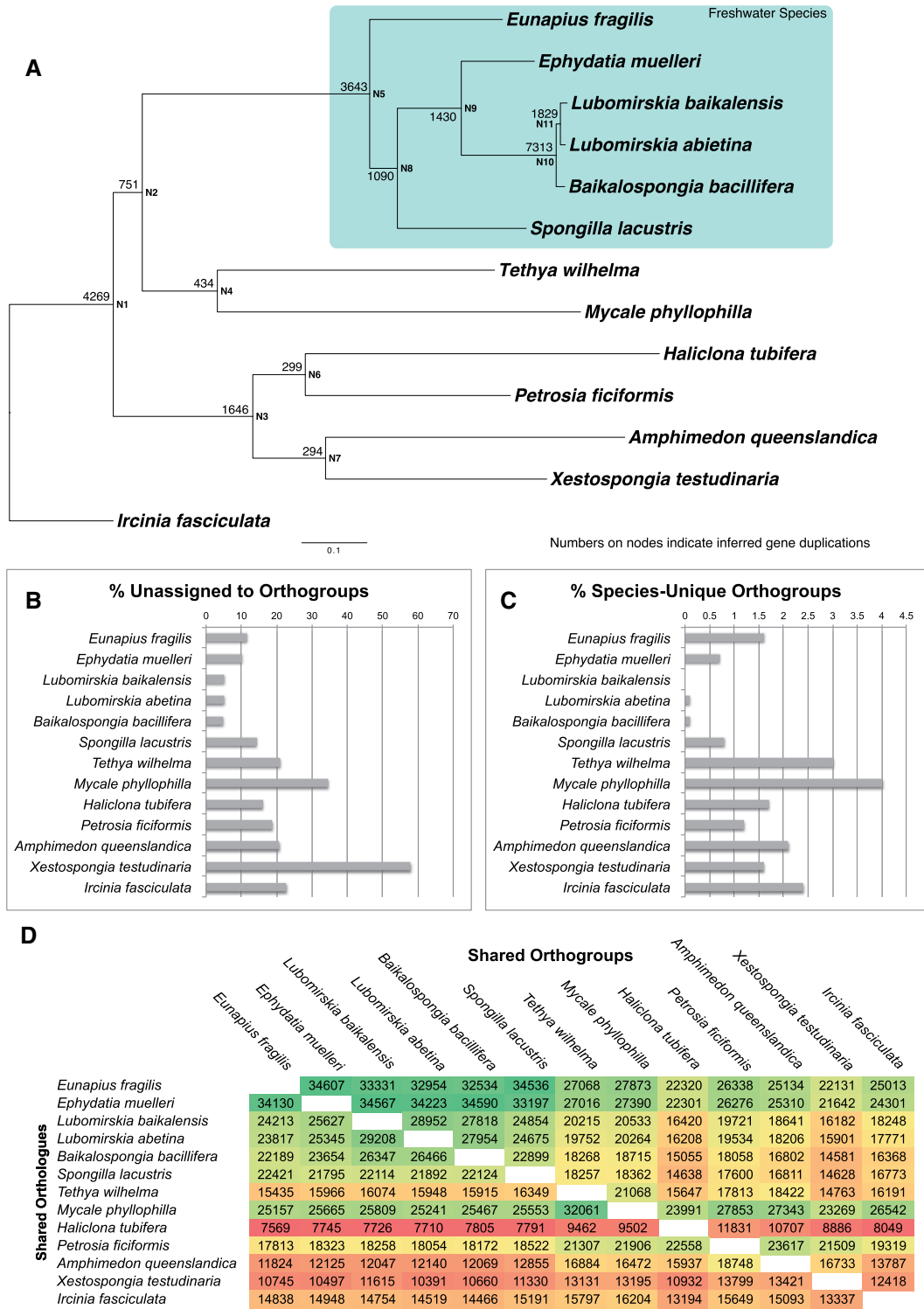


FIG. 6. Analysis of novelties present in freshwater sponge transcriptomes when compared with a range of other genomes and transcriptomes. (A) Phylogeny of freshwater sponges together with marine outgroups used in this analysis. Tree is rooted with *Ircinia fasciculata*. Mapped onto the phylogeny at bases of nodes are the number of duplications that were inferred to map to each node. (B) Contigs unassigned to orthogroups (and thus unique, and single copy, within individual species). (C) orthogroups present only in a single species (and thus unique to the species, but with duplication/alternative isoforms present). (D) Matrix of numbers of orthogroups (top) and orthologs (bottom) shared between species, colored as heat map, with green showing the highest number and red the lowest numbers for each comparison. These numbers are given for every species pair and can be read by finding the names of the species for comparison on the x and y labels, and moving to the site of overlap.

gene cassettes. This is not a consequence of incomplete or inadequate transcriptomic sampling, as the latter two species are represented by genomic sequence. At the other end of the spectrum is *E. fragilis* and *Ep. muelleri* which share the highest similarity, and not, as might be expected, our closely related Lake Baikal sponges.

Summarizing the evidence presented in figure 6, freshwater sponges therefore possess a large number of novel genes (fig. 6A), generated largely through duplication rather than “de novo” (fig. 6B and C). These cassettes are well conserved in freshwater sponges, but Lake Baikal sponges are not the most prominent examples of this (fig. 6D)—other freshwater sponges have more complete gene sets, with better conservation of orthogroups. However, Lake Baikal sponges possess many duplication-derived novelties of their own (fig. 6A) and these are likely to be the source of many of the unique traits possessed by the Lubomirskidae.

Conclusions

The animals of Lake Baikal in general, and the freshwater sponges found there in particular, possess a number of unique biological features. Here, we have presented data, in the form of three deep transcriptomes and a draft genome, allowing further investigations of the biology of these fascinating organisms. Using these, we have examined the adaptation of these sponges to freshwater environments from a number of angles. A disparate, but vital, list of genes shows strong evidence for positive selection, especially in genes related to membrane function and transport. These sponges have used gene duplication to generate the raw material for evolution and have leveraged symbioses to allow them to live in challenging conditions. These findings provide a crucial comparison point when establishing the fundamental requirements, at the molecular level, for evolution to freshwater conditions. Lake Baikal sponges have much to teach us about the myriad demands of adaptation to freshwater and to their unique habitat, and this research will be fruitful for many years to come.

Materials and Methods

Sponge Collection, Nucleic Acid Extraction, Library Construction, and Next-Generation Sequencing

Sponge samples from healthy individuals of the three species studied (one specimen per species) were collected by SCUBA diving in September 2015 in the Southern basin of Lake Baikal near the village of Bolshie Koty (west coast, 51°53′54.4″N 105°04′15.3″E) at 10 m depth. Samples of tissue for RNA extraction were placed in IntactRNA (Evrogen) immediately on return to the surface, incubated at 4 °C overnight, before transfer to a −80 °C freezer for long term storage. Samples for DNA extraction were placed in 100% ethanol and stored at −20 °C. The *L. baikalensis* sample for genomic study was taken from the same individual as the mRNA sample.

RNA extraction was performed using a ExtractRNA kit (Evrogen). An Agilent Technologies 2100 Bioanalyzer or 2200 TapeStation were used to establish that the RNA Integrity Number value was ≥ 8 for samples for sequencing.

RNA libraries were constructed by MacroGen using the TruSeq RNA Sample Prep Kit v2. The HiSeq2000 platform (Illumina, USA) was used for paired-end sequencing at 150 bp.

DNA extraction was performed using a standard CTAB method (Gustincich et al. 1991). DNA quality was assessed by running a subsample on a 1% agarose gel and the quantity of DNA was measured using a NanoVue (GE Healthcare). DNA libraries were constructed by MacroGen using a TruSeq DNA PCR-free library kit (350-bp insert size). An Illumina HiSeq X10 platform was used for sequencing, performed by MacroGen. Initial assessment of read quality and demultiplexing of reads was performed by the provider according to their proprietary procedures. Paired-end reads were made available for download from their server, with no unpaired orphan reads retained by the process.

Initial Quality Assessment

The FastQC program (Andrews 2010) was used to perform initial quality assessment of all reads. The RNA reads required some cleaning, which was performed using Trimmomatic 0.33 (Bolger et al. 2014) with the following settings: ILLUMINACLIP:./Adaptors.fa:2:30:10 LEADING:3 TRAILING:3 SLIDINGWINDOW:4:20 MINLEN:30. The Adaptors.fa file was adjusted to include the adaptor sequences specific to each read pair. Several problems were observed with DNA reads in particular, as detailed in the results. To remedy these, Trimmomatic was first run as described above, before rCorrector (Song and Florea 2015) was used to correct reads. Read pairs for which one of the reads was unfixable were removed using the FilterUncorrectablePEfastq.py script (<https://github.com/harvardinformatics/Last> accessed June 30, 2019). FastQC was then rerun to confirm the quality of reads before assembly. Further, seqtk fqchk (<https://github.com/lh3/seqtk/Last> accessed June 30, 2019) was used to ascertain additional basic metrics.

Assembly and Assessment

Assemblies of RNAseq data were performed using Trinity version 2013_08_14 (Grabherr et al. 2011). Samples from *B. bacillifera* (A2), *L. abietina* (A10), and *L. baikalensis* (A8) were assembled separately. For our genomic data, a variety of assembly methods were trialed at a range of *k* mer sizes. Velvet 1.2.10 (Zerbino and Birney 2008), ABySS 2.0.2 (Simpson et al. 2009), SOAPdenovo2 2.04 (Luo et al. 2012), and SPAdes 3.9.1 (Bankevich et al. 2012) were assayed as noted in the results. Default settings were used with the exception of a minimum contig size of 200 and a minimum coverage of 3 when possible. As these assemblies were to be used for the identification of symbiote and bacterial sequence, no cleaning was performed after assembly.

Numerical metrics relating to assembly were recovered using basic perl and python scripts, available from the authors on request. BUSCO v1.1b1 (Simao et al. 2015) was used to assess the content of both the genome and transcriptomic assemblies, with the completeness of these measured relative to the eukaryotic and metazoan Basic Universal Single-Copy Ortholog (BUSCO) cassettes. *K* mers were counted using

Jellyfish (Marçais and Kingsford 2011) and GenomeScope was used to assay the genome size, heterozygosity, and coverage of the *L. baikalensis* genome sample.

To assess the content of these assemblies further, Blobtools (Laetsch and Blaxter 2017) was run, using Diamond (Buchfink et al. 2015) to run BlastX searches for assignment of taxon identity, against the NCBI *nr* database (*E* value cutoff: 1e-8, with best hit retained). Bowtie2 (Langmead and Salzberg 2012) was used for read mapping. Blobtools was then run using the de novo genome pathway, and with mapping against a local copy of TaxID files.

Gene Identification and Annotation

For individual genes, TblastN (Altschul et al. 1990) was used on a locally constructed database to putatively identify genes using sequences of known homology downloaded from GenBank. To further confirm identity, the sequences thus identified were reciprocally BLASTed (BlastX) against the NCBI *nr* database online using BlastX.

For total annotation, the longest ORF for each contig was translated using the getORF.py python script, retaining only the longest ORF, followed by BlastP annotation (Altschul et al. 1990) against the *nr* protein database. These results were imported into Blast2GO Pro (Götz et al. 2008) followed by InterPro scanning, mapping, annotation (including ANNEX augmentation), and enzyme code mapping. The complete annotations for these are attached as [supplementary file 4, Supplementary Material](#) online.

Phylogenetic Analyses of Symbiont Sequences

The complete 18S rRNA sequence of a potential dinoflagellate symbiont recovered in our genomic sample of *L. baikalensis* (NODE_102849_length_610_cov_109.672) was aligned with 58 other sequences of *Gyrodinium* spp. and uncultured marine and freshwater eukaryotes obtained in NCBI ([supplementary file 5, Supplementary Material](#) online) using Muscle (Edgar 2004) in SeaView v4.0 (Gouy et al. 2010). The phylogenetic analysis was performed using GAMMA + G + I as model of substitution in RAxML v8.0 (Stamatakis 2014) with 10 runs and 100 bootstrap replicates. Also, the sequence of the partial 18S-ITS1 rRNA identified in blast as a Chlorophyta (NODE_291_length_24938_cov_9.23424) was aligned with 57 sequences of other Chlorophyta (including *Choricystis*, *Chlorella*, *Chloroidium*, *Chlorocloster*, *Botryococcus*, *Pseudococcomyxa*, and *Coccomyxa*) obtained in NCBI ([supplementary file 5, Supplementary Material](#) online) using the same alignment strategy as before. Phylogenetic analysis was performed as previously.

Mitochondrial Sequence Identification, Annotation, and Phylogenetic Analysis

TblastN (Altschul et al. 1990) was used to identify mitochondrial sequences (-db_gencode 4) using sequences of known homology from other sponges. This recovered a complete circular mitochondrial sequence after manual alignment and removal of extraneous sequences. Annotation was performed using the MITOS2 webserver (Bernt et al. 2013), with the “04 - Mold/Protozoan/Coelenterate” setting used as the

translational code for sponge data. Manual curation was performed to confirm start/stop codon identity, using homology to known genes to collaborate start/stop location. Mitochondrial phylogeny was inferred based on nucleotide sequence of all of these genes (both protein coding and rRNA), alongside those of known homology downloaded from GenBank. These were aligned on a gene-by-gene basis using MAFFT (Katoh et al. 2002), and the G-INS-i approach. After concatenation with FASConCat-G (Kück and Longo 2014) gaps and regions of poor alignment were excluded and phylogenetic inference was performed using partitioned Bayesian analysis in MrBayes (Ronquist and Huelsenbeck 2003), with models chosen using mixed models in the first instance. The first 25% of samples were discarded as “burn-in,” before the remaining samples were used to generate the figures shown here. Alignments are displayed in Geneious (Kearse et al. 2012) for figure generation.

Selection Test

Transdecoder (Haas et al. 2013), Orthofinder (Emms and Kelly 2018, Diamond, Fasttree, MCL, and MAFFT options) and Phylotreepruner (Kocot et al. 2013) were run sequentially to identify a data set of orthologous gene alignments. Final alignments, after pruning, are represented by only one sequence per species (i.e., no paralogous sequence). Concatenated amino acid sequence from these alignments were used as the basis for partitioned Bayesian analysis in MrBayes (Ronquist and Huelsenbeck 2003) to determine a species tree for selection tests (shown in [fig. 4A](#)), with a GTR + 4G model applied to each gene in an independent partition. Selection tests were performed according to a schema put forward in Santagata (2018). PAL2NAL (Suyama et al. 2006) was then run orthogroup-by-orthogroup to find the CDS region corresponding to the aligned protein sequence, and generate a nucleotide alignment for performing selection tests.

CODEML was run in PAML (Muse and Gaut 1994; Yang 2007) to test null versus alternative hypotheses as to gene-level selection, and differences in LnL used as the basis for χ^2 tests of level of significance. These were corrected for multiple comparison false discovery rate (FDR) using Benjamini and Hochberg correction (Benjamini and Hochberg 1995; Benjamini and Yekutieli 2001). BEB values in the ALT output were also extracted and used to identify sites under selection (Yang et al. 2005). HyPhy was run, with BUSTED, aBSREL, and MEME tests of branch-level and site-level selection, respectively (Pond et al. 2005; Murrell et al. 2012, 2015; Smith et al. 2015). Sequences were annotated by BlastP identity to the *nr* database.

GO Overrepresentation Analysis

To identify GO terms overrepresented in the gene set noted as under selection by all tests, we used the ShinyGO (Ge and Jung 2018) tool. The accession numbers of the *A. queenslandica* orthologs within the positively selected orthogroups were input into ShinyGo, with a *P* value cutoff for FDR of 0.05. ShinyGO automatically retrieved the GO terms for these genes from the annotated *A. queenslandica* resource,

determined enriched GO terms within this set and corrected for FDR. The results of overrepresentation analyses, alongside network diagrams, were downloaded from the ShinyGO server. To visualize overenriched GO complements, the Revigo tool (Supek et al. 2011) was used to display this data, with these settings: List: Medium 0.7, database: whole Uniprot, and Semantic similarity: Simrel. This was exported as an R plot, and a pdf generated. Font and colour was edited in Adobe Illustrator (Adobe: San Jose, CA) for display.

Novelty Identification

To identify novelties shared across freshwater sponges, but absent from outgroups, we used the same data sets as used for the selection tests described above, with the addition of the protein sets from the genomes of *X. testudinaria* (Ryu et al. 2016) and *Tethya wilhelmi* (Francis et al. 2017) to compare with complete gene sets as outgroups. Orthofinder2 (Emms and Kelly 2018) was run to identify orthogroups (settings: Diamond, Fasttree, MCL, and MAFFT), and to identify those found uniformly in freshwater data sets, but not in outgroups. These data were used to extract data on gene duplication at nodes, statistics regarding numbers of genes assigned to orthogroups, and shared orthogroup and ortholog figures, as displayed in figure 6.

Supplementary Material

Supplementary data are available at *Molecular Biology and Evolution* online.

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Author Contributions

V.B.I. conceived of the study, gathered specimens, and performed RNA and DNA extractions. N.J.K., B.P., A.R., and V.B.I. designed and performed experiments. B.P. performed mitochondrial data analysis. N.J.K. performed assembly and bioinformatic analysis. All authors wrote and agreed on the final form of the article.

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