290 Metagenome-assembled Genomes from the Mediterranean Sea: Ongoing Effort to Generate Genomes from the *Tara Oceans* Dataset

Authors
Benjamin J. Tully[1‡], Rohan Sachdeva[2], Elaina D. Graham[2], and John F. Heidelberg[1,2]

‡ - corresponding author, tully.bj@gmail.com
1 – Center for Dark Energy Biosphere Investigations, University of Southern California, Los Angeles, CA 90089
2 – Department of Biological Sciences, University of Southern California, Los Angeles, CA 90089

Abstract
The *Tara Oceans* Expedition has provided large, publicly-accessible microbial metagenomic datasets from a circumnavigation of the globe. Utilizing several size fractions from the samples originating in the Mediterranean Sea, we have used current assembly and binning techniques to reconstruct 290 putative high-quality metagenome-assembled bacterial and archaeal genomes, with an estimated completion of ≥50%, and an additional 2,786 bins, with estimated completion of 0-50%. We have submitted our results, including initial taxonomic and phylogenetic assignments for the putative high-quality genomes, to open-access repositories (iMicrobe and FigShare) for the scientific community to use in ongoing research.

Introduction

Microorganisms are a major constituent of the biology within the world's oceans and act as the important linchpins in all major global biogeochemical cycles[1]. Marine microbiology is among the disciplines at the forefront of pushing advancements in understanding how microorganisms respond to and impact the local and large-scale environments. An estimated 10^{29} Bacteria and Archaea[2] reside in the oceans and an immense amount of poorly constrained, and ever evolving genetic diversity.

The *Tara Oceans* Expedition (2003-2010) encompassed a major endeavor to add to the body of knowledge collected during previous global ocean surveys to sample the genetic potential of microorganisms [3]. To accomplish this goal, members of *Tara Oceans* sampled planktonic organisms (viruses to fish larvae) at two major depths, the surface ocean and the mesopelagic. The amount of data collected was expansive and included 35,000 samples from 210 ecosystems[3]. The *Tara Oceans* Expedition generated and publically released 7.2 Tbp of metagenomic data from 243 ocean samples from throughout the global ocean, specifically targeting the smallest members of the ocean biosphere, the viruses, Bacteria and Archaea, and picoeukaryotes[4]. Initial work on these fractions produced a large protein database, totaling > 40 million nonredundant protein sequences and identified >35,000 microbial operational taxonomic units (OTUs)[4].

Leveraging the publically available metagenomic sequences from the "girus" (giant virus; 0.22-1.6 μm), "bacteria" (0.22-1.6 μm), and "protist" (0.8-5 μm) size fractions, we have performed a new joint assembly of these samples using current sequence assemblers (Megahit[5]) and methods (combining assemblies from multiple sites using Minimus2[6]). These metagenomic assemblies were binned using a strictly coverage based binning algorithm[7] in to 290 high-quality (low contamination) microbial genomes, ranging from 50-100% estimated completion.

Environmentally derived genomes representing the most abundant microorganisms are imperative for a number of downstream applications, including comparative genomes, metatranscriptomics, and metaproteomics. This series of genomic data can allow for the recruitment of environmental "-omic" data and provide linkages between functions and phylogenies. This method was initially performed on the seven sites from the Mediterranean Sea containing microbial metagenomic samples (TARA007, -009, -018, -023, -025 and -030), but will continue through the various Longhurst provinces[8,9] sampled during the *Tara Oceans* project (Figure 1). All of the assembly data is publically available, including the initial Megahit assemblies for each site from the various size fractions and depths and putative (minimal quality control) genomes within iMicrobe (http://imicrobe.us).

Materials and Methods

A generalized version of the following workflow is presented in Figure 2.

Sequence Retrieval and Assembly

All sequences for the reverse and forward reads from each sampled site and depth within the Mediterranean Sea were accessed from European Molecular Biology Laboratory (EMBL) utilizing their FTP service (Table 1). Paired-end reads from different filter sizes from each site and depth (e.g., TARA0007, girus filter fraction, sampled at the deep chlorophyll maximum) were assembled using Megahit[5] (v1.0.3; parameters: --preset, meta-sensitive). To keep consistent with TARA sample nomenclature, "bacteria" or "BACT" will be used to encompass the size fraction 0.22-1.6 μm. All of the Megahit assemblies were pooled in to two tranches based on assembly size, ≤1,999bp, and ≥2,000bp. Longer assemblies (≥2kb) with ≥99% semi-global identity were combined using CD-HIT-EST (v4.6; -T 90 -M 500000 -c 0.99 -n 10). The reduced set of contiguous DNA fragments (contigs) was then cross-assembled using Minimus2[6] (AMOS v3.1.0; parameters: -D OVERLAP=100 MINID=95).

Metagenome-assembled Genomes

Sequence reads were recruited against a subset of contigs (≥7.5kb) constructed during the secondary assembly (Megahit + Minimus2) for each of the *Tara* samples using Bowtie2[10] (v4.1.2; default parameters). Utilizing the SAM file output, read counts for each contig were determined using featureCounts[11] (v1.5.0; default parameters). Coverage was determined for all contigs by dividing the number of recruited reads by the length of the contig (reads/bp). Due to the low coverage nature of the samples, in order to effectively delineate between contig coverage patterns, the coverage values were transformed by multiplying by five (determined through manual tuning). Transformed coverage values were then utilized to cluster contigs in to bins utilizing BinSanity (parameters: -p -3, -m 4000, -v 400, -d 0.9) [7]. Bins were assessed for the presence of putative microbial genomes using CheckM[12] (v1.0.3; parameters: lineage_wf). Bins were split in to three categories: (1) putative high quality genomes (≥50% complete and ≤10% cumulative redundancy [% contamination – (% redundancy × % strain heterogeneity ÷ 100)]); (2) bins with "high" contamination (≥50% complete and ≥10% cumulative redundancy); and (3) low completion bins (<50% complete). The high contamination group were additionally binned using the BinSanity refinement method (refine-contaminated-log.py; parameters: -p 'variable', -m 2000, -v 200, -d 0.9), which utilizes affinity propagation[13] to cluster contigs within a bin based on tetranucleotide frequencies and %G+C.

To determine the preference values needed to successfully bin the high contamination bins, 15 bins were assessed manually using the number of marker occurrences determined by CheckM. Bins containing approximately two genomes, three genomes, and bins with more genomes used a preference of -1000 (-p -1000), -500 (-p -500), and -100 (-p -100), respectively. The 15 manually assessed bins were used to train a decision tree within scikit-learn[14] (default parameters, DecisionTreeClassifier) to assign parameters to the other bins. The resulting bins were added to one of the three categories: putative high quality genomes, high contamination bins, and low completion bins. The high contamination bins were processed for a third time with the BinSanity refinement step utilizing a preference of -100 (-p -100). These bins were given final assignments to either the putative high quality genomes (some putative genomes had >10% cumulative contamination, but have been designated) or low completion bins. Bins determined to be low completion bins were reserved for an additional round of binning (see below).

After this initial round of binning, all contigs not assigned to putative high-quality genomes were assessed using BinSanity using raw coverage values. Two additional rounds of refinement were performed (as above) with the first round of refinement using the decision tree to determine preference and the second round using a set preference of -10 (-p -10). Following this binning phase, contigs were assigned to high quality bins (*e.g.*, ***Tara*** **Med**iterranean genome 1, referred to as TMED1, etc.), low completion bins with at least five contigs (0-50% complete; TMEDlc1, etc. lc, **l**ow **c**ompletion), or were not placed in a bin (Supplemental Table 1 & 2).

Taxonomic and Phylogenetic Assignment of High Quality Genomes

The bins representing the high quality genomes were assessed for taxonomy and phylogeny using multiple methods to provide a quick reference for selecting genomes of interest. Taxonomy as assigned using the putative placement provided via CheckM during the pplacer[15] step of the analysis to the lowest taxonomic placement (parameters: tree_qa -o 2). This step was also performed for all low completion bins. A second taxonomic assignment was determined using a method modified from Albersten, *et al*. (2013)[16], wherein putative coding DNA sequences (CDSs) were determined using Prodigal[17] (v2.6.3; parameters: -m -o -p meta -q). The putative CDS were searched against the NCBI non-redundant (NR) database (accessed March 2016) using DIAMOND[18] (v0.8.11.73; parameters: -f xml -k 5 --sensitive -e 1e-10) and the output was processed using MEGAN[19] (v4; parameters: recompute toppercent = 5, recompute minsupport = 1, collapse rank = species, select nodes = all) to determine the last common ancestor for the top five matches. Using a script from the Multi-Metagenome package (hmm.majority.vote.pl; https://github.com/MadsAlbertsen/multimetagenome; parameters: -n -l 4 [-l 5, -l 6, or -l 7]), each contig was assigned a consensus taxonomic identification at approximately the Phylum, Class, Order, and Family levels. A consensus for all contigs at each taxonomic level was determined. If at any level a tie was achieved between possible assignments, it has been denoted with a “T” in the genome table.

Two separate attempts were made to assign the high quality genomes a phylogenetic assignment. High quality genomes were searched for the presence of the full-length 16S rRNA gene sequence using RNAmmer[20] (v1.2; parameters: -S bac -m ssu). All full-length sequences were aligned to the SILVA SSU reference database (Ref123) using the SINA web portal aligner[21] (https://www.arb-silva.de/aligner/). These alignments were loaded in to ARB[22] (v6.0.3), manually assessed, and added to the non-redundant 16S rRNA gene database (SSURef123 NR99) using ARB Parsimony (Quick) tool (parameters: default). A selection of the nearest neighbors to the *Tara* genome sequences were selected and used to construct a 16S rRNA

phylogenetic tree. Genome-identified 16S rRNA sequences and SILVA reference sequences were aligned using MUSCLE[23] (v3.8.31; parameters: -maxiters 8) and processed by the automated trimming program trimAL[24] (v1.2rev59; parameters: -automated1). Automated trimming results were assessed manually in Geneious[25] (v6.1.8) and trimmed where necessary (positions with >50% gaps) and re-aligned with MUSCLE (parameters: -maxiters 8). An approximate maximum likelihood (ML) tree with pseudo-bootstrapping was constructed using FastTree[26] (v2.1.3; parameters: -nt -gtr -gamma; Figure 3).

High-quality genomes were assessed for the presence of the 16 ribosomal markers genes used in Hug, *et al*. (2016)[27]. Putative CDSs were determined using Prodigal (v2.6.3; parameters: -m -p meta) and were searched using HMMs for each marker using HMMER[28] (v3.1b2; parameters: hmmsearch --cut_tc --notextw). If a genome had multiple copies of any single marker gene, neither was considered, and only genomes with ≥8 markers were used to construct a phylogenetic tree. Markers identified from the high quality genomes were combined with markers from 1,729 reference genomes that represent the major bacterial phylogenetic groups (as presented by IMG[29]). Archaeal reference sequences were not included; however, none of the putative archaeal environmental genomes had a sufficient number of markers for inclusion on the tree. Each marker gene was aligned using MUSCLE (parameters: -maxiters 8) and automatically trimmed using trimAL (parameters: -automated1). Automated trimming results were assessed (as above) and re-aligned with MUSCLE, as necessary. Final alignments were concatenated and used to construct an approximate ML tree with pseudo-bootstrapping with FastTree (parameters: -gtr -gamma; Figure 4).

Relative Abundance of High Quality Genomes

To set-up a baseline that could approximate the "microbial" community (Bacteria, Archaea and viruses) present in the various *Tara* metagenomes, which included filter sizes specifically targeting both protists and giruses, reads were recruited against all contigs generated from the Minimus2 and Megahit assemblies ≥2kb using Bowtie2 (default parameters). Some assumptions were made that contigs <2kb would include, low abundance bacteria and archaea, bacteria and archaea with high degrees of repeats/assembly poor regions, fragmented picoeukaryotic genomes, and problematic read sequences (low quality, sequencing artefacts, etc.). All relative abundance measures are relative to the number of reads recruited to the assemblies ≥2kb. Read counts were determined using featureCounts (as above). Length-normalized relative abundance values were determined for each high quality genome for each sample:

$$\frac{\frac{Reads}{bp}\,per\ genome}{\sum \frac{Reads}{bp}\,all\ genomes} \times \frac{\sum Recruited\ reads\ to\ genomes}{\sum Recruited\ reads\ to\ all\ contigs\ (\geq 2kb)} \times 100$$

Available Through iMicrobe

In keeping with the open-access nature of the *Tara Oceans* project, all of the data generated for this analysis is publically available through iMicrobe (http://data.imicrobe.us/project/view/261), including: all contigs generated using Megahit from each sample; all contigs from Minimus2 + Megahit output used for binning and community assessment, ≥2kb and ≥7.5kb; a table that details statistics, taxonomy, and phylogeny for the high quality genomes; the putative genome contigs and Prodigal-predicted nucleotide and protein putative CDS FASTA files. Additional files, such as, the ribosomal marker HMM profiles, reference genome markers, high quality genome markers, final concatenated MUSCLE alignment, FastTree Newick file, contig read

count data, relative abundance matrix for genomes from all samples, low completion bins, and contigs without a bin, as well as, additional data files, have been provided and are available through FigShare (https://dx.doi.org/10.6084/m9.figshare.3545330). Digital locations of data files and contents can be found on Supplemental Table 3.

Results

Assembly

The initial Megahit assembly was performed on the publicly available reads for *Tara* stations 007, 009, 018, 023, 025, 030. Starting with 147-744 million reads per sample, the Megahit assembly process generated 1.2-4.6 million assemblies with a mean N_{50} and longest contig of 785bp and 537kb, respectively (Table 1). In general, the assmeblies generated from the *Tara* samples targeting the protist size fraction (0.8-5 μm) had a shorter N_{50} value than the bacteria size fractions (mean: 554bp vs 892bp, respectively). Assemblies from the Megahit assembly process were pooled and separated by length. Of the 42.6 million assemblies generated during the first assembly, 1.5 million were ≥2kb in length (Table 2). Several attempts were made to assemble the shorter contigs, but publicly available overlap-consensus assemblers (Newbler [454 Life Sciences], cap3[30], and MIRA[31]) failed on multiple attempts. Processing the ≥2kb assemblies from all of the samples through CD-HIT-EST reduced the total to 1.1 million contigs ≥2kb. This group of contigs was subjected to the secondary assembly through Minimus2, generating 158,414 new contigs (all ≥2kb). The secondary contigs were combined with the Megahit contigs that were not assembled by Minimus2. This provided a contig dataset consisting of 660,937 contigs, all ≥2kb in length (Table 2; further referred to as data-rich-contigs).

Binning

The set of data-rich-contigs was used to recruit the metagenomic reads from each sample using Bowtie2. The data-rich-contigs recruited 15-81% of the reads depending on the sample. In general, the protist size fraction recruited substantially fewer reads than the girus and bacteria size fractions (mean: 19.8% vs 75.0%, respectively) (Table 1). For the protist size fraction, the "missing" data for these recruitments likely results from the poor assembly of more complex and larger eukaryotic genomes. The fraction of the reads that do not recruit in the girus and bacterial size fraction samples could be accounted for by the large number of low quality assemblies (200-500bp) and reads that could not be assembled due to low abundance or high complexity (Table 2). Coverage was determined as total reads per base pair, based on the number of reads recruited to each contig.

Unsupervised binning was performed using both transformed and raw coverage values for a subset of 95,506 contigs from the data-rich-contigs that were ≥7.5kb (referred to further as binned-contigs) utilizing the tool BinSanity. An iterative process was performed that first used coverage to generate putative bins, and then after removing putative high-quality genomes (≥50% complete and <10% redundancy), based on estimates of redundancy through CheckM, used two passes through the BinSanity refinement process, utilizing sequence composition. Binning using the transformed coverage data generated 237 putative high-quality genomes (12 putative genomes are of slightly lower quality with >10% redundancy and have been noted) containing 15,032 contigs. Contigs not in putative genomes were re-binned through the iterative use of BinSanity based on raw coverage values, generating 53 additional putative high-quality genomes encompassing 3,348 contigs. In total, 290 putative high-quality genomes were generated with 50-100% completion (mean: 69%) with a mean length and number of putative

229 CDS of 1.7Mbp and 1,699, respectively (iMicrobe; Supplemental Table 1). All other contigs
230 were grouped in to bins with at least five contigs, but with estimated completion of 0-50% (2,786
231 low completion bins; 74,358 contigs; Supplemental Table 2) or did not bin (2,732 contigs).
232 Nearly a quarter of the low completion bins (24.7%) have an estimated completion of 0%.
233
234 *Taxonomy, Phylogeny, & Potential Organisms of Interest*
235 The 290 putative high-quality genomes had a taxonomy assigned to it via CheckM during the
236 pplacer step. All of the genomes, except for 20, had an assignment to at least the Phylum level,
237 and 83% of the genomes had an assignment to at least the Class level. Additionally, all of the
238 genomes were assigned putative taxonomies using a consensus method of the taxonomies
239 assigned to the putative CDS on a contig. The genomes were assigned four levels of taxonomic
240 information, roughly equivalent to Phylum, Order, Class, and Family. Due to the nature of this
241 method, especially at lower taxonomic levels, it is possible for a small number of assignments to
242 greatly influence the results. Because all of these methods have inherent biases, consistency
243 across several results should be viewed as reinforcing support for the accuracy of the genome,
244 while inconsistent results should not be used as evidence of an incorrectly binned genome.
245 Attempts were made to provide phylogenetic information for as many genomes as
246 possible. Genomes were assessed for the presence of full-length 16S rRNA genes. In total, 37
247 16S rRNA genes were detected in 35 genomes (mean 16S rRNA gene copy number, 1.05). 16S
248 rRNA genes can prove to be problematic during the assembly steps due the high level of
249 conservation that can break contigs[32] (Figure 3). Additionally, the conserved regions of the 16S
250 rRNA, depending on the situation, can over- or under-recruit reads, resulting in coverage
251 variations that can misplace contigs in to the incorrect genome. As such, several of the 16S
252 rRNA phylogenetic placements support the taxonomic assignments, while some are
253 contradictory. Further analysis should allow for the determination of the most parsimonious
254 result.
255 Beyond the 16S rRNA gene, genomes were searched for 16 conserved, syntenic
256 ribosomal markers. Sufficient markers (≥8) were identified in 193 of the genomes (67%) and
257 placed on a tree with 1,729 reference sequences (Figure 4). Phylogenies were then assigned to
258 the lowest taxonomic level that could be confidently determined.
259 The taxonomic and phylogenetic assignments are provided to give downstream users a
260 guide for determining which genomes prove to be most interesting for further analysis. Highest
261 confidence should be given to genomes with multiple lines of evidence supporting an assignment
262 and additional confirmation should be gathered for those with multiple conflicting results. These
263 putative results reveal a number of genomes were generated that represent multiple clades for
264 which environmental genomic information remains limited, including: *Planctomycetes*,
265 *Verrucomicrobia*, *Marinimicrobia*, *Cyanobacteria*, and uncultured groups within the *Alpha*- and
266 *Gammaproteobacteria*.
267
268 *Relative Abundance*
269 Based on the assembly and recruitment results, the assumption was made that the data-rich-
270 contigs and their corresponding reads represent the dominant portion of the microbial (bacterial,
271 archaeal, and viral) community and that reads that did not recruit represent eukaryotes, low
272 quality assemblies, and/or less dominant portions of the microbial community. A length-
273 normalized relative abundance value was determined for each genome in each sample based on

the number of reads recruited to the data-rich-contigs. The relative abundance for the individual genomes was determined based on this portion of the read dataset.

In general, the genomes and their underlying contigs had low coverage (<1X coverage) and low relative abundance (maximum relative abundance = 1.9% for TMED155 a putative *Cyanobacteria* in TARA023-PROT-SRF; Supplemental Table 1). The high-quality genomes accounted for 1.57-25.16% of the approximate microbial community as determined by the data-rich-contigs (mean = 13.69%), with the ten most abundant genomes representing 0.61-10.31% (Table 1).

Almost all of the contigs in the binned-contigs were low coverage, only a small subset of 6,350 contigs (6.6%) had >1X coverage in at least one sample. Of these contigs, 1,962 were assigned to putative high-quality genomes, while the other contigs were placed in the low completion bins. Further, an additional 22,470 contigs (Total bp = 79,422,500bp, mean = 3,535bp, and longest contig = 7,498bp) within data-rich-contigs (1.3%) had greater than >1X coverage, but were not included in the binning protocol.

Concluding Statement

The goal of this project was to provided preliminary putative genomes from the *Tara Oceans* microbial metagenomic datasets. The 290 putative high-quality genomes and 2,786 low completion bins were created using the 20 samples and six stations from the Mediterranean Sea. We will continue to generate putative high-quality genomes from additional *Tara Oceans* dataset, starting with the Red Sea and Arabian Sea in the near future.

We would like to take some time to highlight to interesting results created within this dataset. For new genomes from environmental organisms, this project created approximately 14 new *Cyanobacteria* genomes within the genera *Prochlorococcus* and *Synechococcus* and 33 new SAR11 genomes. Three unconfirmed members related to the Candidate Phyla Radiation (CPR) as determined by placement of an internal node between the *Parcubacteria* and *Microgenomates* (with long-branch characteristics; TMED88) and a node basal to the CPR genomes, potentially related to the *Wirthbacteria* (TMED70 and TMED22), on the concatenated ribosomal marker tree. Additionally, there are putative genomes from the marine *Euryarchaeota* (n = 11), *Verrucomicrobia* (n = 17), *Planctomycetes* (n = 14), and *Marinimicrobia* (n ≈ 5).

Some additional perplexing results include, TMED58 a putative *Deltaproteobacteria* with taxonomic assignments from the NCBI NR database to the *Myoviridae*. This result occurs due the presence of a few large contigs assigned to the bacteria and many small contigs assigned to the virus. However, if these two entities should be binned together remains unresolved. Lastly, the low completion bins may house distinct viral genomes. Of particular interest may be the 40 bins with 0% completion (based on single-copy marker genes), but that contain >500kb of genetic material (including 3 bins with >1Mb). These large bins lacking markers may be good candidates for research in to the marine "giant viruses" and episomal DNA sources (plasmids, etc.).

It should be noted, researchers using this dataset should be aware that all of the genomes generated from these samples (and additional stations, which are on-going) should be used as a resource with some skepticism towards the results being an absolute. Like all results for metagenome-assembled genomes, these genomes represent a best-guess approximation of a taxon from the environment[33]. Researchers are encouraged to confirm all claims through various genomic analyses and accuracy may require the removal of conflicting sequences.

Acknowledgements
We would like to thank iMicrobe and FigShare for hosting data for this research. We are indebted to the *Tara Oceans* project and team for their commitment to open-access data that allows data aficionados to indulge in the data and attempt to add to the body of science contained within. And we thank the Center for Dark Energy Biosphere Investigations (C-DEBI) for providing funding to BJT and JFH (OCE-0939654).

Author Contributions
BJT conceived of the project, performed all of the methods and analyses, and wrote the manuscript. RS provided the origins of the workflow and invaluable feedback during the execution of the methods and analyses. EDG provided feedback and troubleshooting using the pre-release version of BinSanity. JFH provided funding. RS and JFH contributed to manuscript editing and polishing. All authors have read the submitted draft of the manuscript.

Legends

Table 1. Megahit sequencing, recruitment to Megahit + Minimus2 contigs ≥2kb, and relative abundance of high-quality genome results for each sample

Table 2. Statistics and the number contigs/assemblies at various steps during processing

Figure 1. Map illustrating the locations and size fractions sampled for the *Tara Oceans* Mediterranean Sea datasets. Girus, 'giant virus' size fraction (0.22-1.6 µm). Bact, 'bacteria' size fraction (0.22-1.6 µm). Prot, 'protist' size fraction (0.8-5.0 µm).

Figure 2. Workflow used to process *Tara Oceans* Mediterranean Sea metagenomic datasets.

Figure 3. FastTree approximate maximum-likelihood phylogenetic tree constructed with 37 and 785 16S rRNA genes from putative high-quality genomes and references, respectively.

Figure 4. Cladogram of a FastTree approximate maximum-likelihood phylogenetic tree constructed using 16 syntenic, single-copy marker genes for 193 high-quality genomes and 1,729 reference genomes. Leaves denoting the position of the TMED genomes have been indicated by extending beyond the edge of the tree.

Supplemental Table 1. Statistics and taxonomic and phylogenetic assignments for the putative high-quality genomes

Supplemental Table 2. Statistics and CheckM taxonomy for low completion bins

Supplemental Table 3. Data file names, descriptions, and digital locations

References

1. Falkowski, P. G., Fenchel, T. & DeLong, E. F. The Microbial Engines That Drive Earth's Biogeochemical Cycles. *Science* **320,** 1034–1039 (2008).

366 2. Whitman, W. B., Coleman, D. C. & Wiebe, W. J. Prokaryotes: The unseen majority. *Proc.*
367 *Natl. Acad. Sci. U.S.A.* **95,** 6578–6583 (1998).
368 3. Karsenti, E. *et al.* A Holistic Approach to Marine Eco-Systems Biology. *Plos Biol* **9,**
369 e1001177–5 (2011).
370 4. Sunagawa, S. *et al.* Ocean plankton. Structure and function of the global ocean
371 microbiome. *Science* **348,** 1261359–1261359 (2015).
372 5. Li, D. *et al.* MEGAHIT v1.0: A fast and scalable metagenome assembler driven by
373 advanced methodologies and community practices. *Methods* **102,** 3–11 (2016).
374 6. Treangen, T. J., Sommer, D. D., Angly, F. E., Koren, S. & Pop, M. Next generation
375 sequence assembly with AMOS. *Curr Protoc Bioinformatics* **Chapter 11,** Unit 11.8
376 (2011).
377 7. Graham, E. D., Heidelberg, J. F. & Tully, B. J. BinSanity: Unsupervised Clustering of
378 Environmental Microbial Assemblies Using Coverage and Affinity Propagation. *bioRxiv*
379 (2016). doi:10.1101/069567
380 8. Longhurst, A., Sathyendranath, S., Platt, T. & Caverhill, C. An Estimate of Global
381 Primary Production in the Ocean From Satellite Radiometer Data. *Journal of Plankton*
382 *Research* **17,** 1245–1271 (1995).
383 9. Longhurst, A. *PROVINCES: THE SECONDARY COMPARTMENTS. Ecological*
384 *Geography of the Sea* 103–114 (Elsevier Inc., 2006). doi:10.1016/B978-0-12-455521-
385 1.50008-5
386 10. Langmead, B. & Salzberg, S. L. Fast gapped-read alignment with Bowtie 2. *Nat Meth* **9,**
387 357–359 (2012).
388 11. Liao, Y., Smyth, G. K. & Shi, W. featureCounts: an efficient general purpose program for
389 assigning sequence reads to genomic features. *Bioinformatics* **30,** 923–930 (2014).
390 12. Parks, D. H., Imelfort, M., Skennerton, C. T., Hugenholtz, P. & Tyson, G. W. CheckM:
391 assessing the quality of microbial genomes recovered from isolates, single cells, and
392 metagenomes. *Genome Res.* **25,** 1043–1055 (2015).
393 13. Frey, B. J. & Dueck, D. Clustering by passing messages between data points. *Science* **315,**
394 972–976 (2007).
395 14. Pedregosa, F. *et al.* Scikit-learn: Machine Learning in Python. *Journal of Machine*
396 *Learning Research* **12,** 2825–2830 (2011).
397 15. Matsen, F. A., Kodner, R. B. & Armbrust, E. V. pplacer: linear time maximum-likelihood
398 and Bayesian phylogenetic placement of sequences onto a fixed reference tree. *BMC*
399 *Bioinformatics* **11,** 538 (2010).
400 16. Albertsen, M. *et al.* Genome sequences of rare, uncultured bacteria obtained by
401 differential coverage binning of multiple metagenomes. *Nat Biotechnol* **31,** 533–538
402 (2013).
403 17. Hyatt, D., LoCascio, P. F., Hauser, L. J. & Uberbacher, E. C. Gene and translation
404 initiation site prediction in metagenomic sequences. *Bioinformatics* **28,** 2223–2230
405 (2012).
406 18. Buchfink, B., Xie, C. & Huson, D. H. Fast and sensitive protein alignment using
407 DIAMOND. *Nat Meth* **12,** 59–60 (2014).
408 19. Huson, D. H., Mitra, S., Ruscheweyh, H.-J., Weber, N. & Schuster, S. C. Integrative
409 analysis of environmental sequences using MEGAN4. *Genome Res.* **21,** 1552–1560
410 (2011).
411 20. Lagesen, K. *et al.* RNAmmer: consistent and rapid annotation of ribosomal RNA genes.

412 *Nucleic Acids Res.* **35,** 3100–3108 (2007).
413 21. Pruesse, E., Peplies, J. & Glöckner, F. O. SINA: accurate high-throughput multiple
414 sequence alignment of ribosomal RNA genes. *Bioinformatics* **28,** 1823–1829 (2012).
415 22. Ludwig, W. *et al.* ARB: a software environment for sequence data. *Nucleic Acids Res.* **32,**
416 1363–1371 (2004).
417 23. Edgar, R. C. MUSCLE: multiple sequence alignment with high accuracy and high
418 throughput. *Nucleic Acids Res.* **32,** 1792–1797 (2004).
419 24. Capella-Gutiérrez, S., Silla-Martínez, J. M. & Gabaldón, T. trimAl: a tool for automated
420 alignment trimming in large-scale phylogenetic analyses. *Bioinformatics* **25,** 1972–1973
421 (2009).
422 25. Kearse, M. *et al.* Geneious Basic: an integrated and extendable desktop software platform
423 for the organization and analysis of sequence data. *Bioinformatics* **28,** 1647–1649 (2012).
424 26. Price, M. N., Dehal, P. S. & Arkin, A. P. FastTree 2--approximately maximum-likelihood
425 trees for large alignments. *PLoS ONE* **5,** e9490 (2010).
426 27. Hug, L. A. *et al.* A new view of the tree of life. *Nature Microbiology* 1–6 (2016).
427 doi:10.1038/nmicrobiol.2016.48
428 28. Finn, R. D., Clements, J. & Eddy, S. R. HMMER web server: interactive sequence
429 similarity searching. *Nucleic Acids Res.* **39,** W29–W37 (2011).
430 29. Markowitz, V. M. *et al.* The integrated microbial genomes (IMG) system. *Nucleic Acids*
431 *Res.* **34,** D344–8 (2006).
432 30. Huang, X. & Madan, A. CAP3: A DNA sequence assembly program. *Genome Res.* **9,**
433 868–877 (1999).
434 31. Chevreux, B. *et al.* Using the miraEST assembler for reliable and automated mRNA
435 transcript assembly and SNP detection in sequenced ESTs. *Genome Res.* **14,** 1147–1159
436 (2004).
437 32. Miller, J. R., Koren, S. & Sutton, G. Assembly algorithms for next-generation sequencing
438 data. *Genomics* **95,** 315–327 (2010).
439 33. Sharon, I. & Banfield, J. F. Microbiology. Genomes from metagenomics. *Science* **342,**
440 1057–1058 (2013).
441
442

Table 1. Megahit sequencing, recruitment to Megahit + Minimus2 contigs ≥2kb, and relative abundance of high-quality genome results for each sample

TARA Sample Site	Size Fraction (Girus, Bacteria, or Protist)	Depth (Surface or DCM*)	No. of reads	No. of initial Megahit assembly	N50ª (bp; initial Megahit assembly)	Longest initial Megahit assembly (bp)	Recruitment (% to ≥2kb Megahit+Minimus2 contigs)	Relative abundanceº of high-quality genomes (%)	Relative abundanceº of ten most abundant genomes (%)
TARA007	Girus	DCM	178,519,830	1,318,470	828	220,754	72.84	14.64	6.35
TARA007	Girus	Surface	221,166,612	1,308,847	861	211,946	81.74	14.83	6.12
TARA007	Protist	DCM	744,458,992	4,667,618	654	188,635	19.45	8.60	3.18
TARA007	Protist	Surface	265,432,098	2,590,120	564	18,444	25.58	1.57	0.61
TARA009	Girus	DCM	416,553,274	2,796,841	831	1,643,839	69.48	14.16	6.32
TARA009	Girus	Surface	489,617,426	1,787,467	929	1,142,851	68.85	12.29	4.76
TARA009	Protist	DCM	329,036,110	1,938,636	613	95,724	22.07	13.35	4.20
TARA009	Protist	Surface	370,813,078	1,700,350	588	292,050	22.53	15.97	6.17
TARA018	Bacteria	DCM	408,021,182	2,520,645	840	1,573,060	76.22	11.49	3.18
TARA018	Bacteria	Surface	414,976,308	2,604,031	816	2,086,508	75.80	11.03	3.02
TARA023	Bacteria	DCM	147,400,552	1,273,576	830	213,456	76.08	13.29	4.09
TARA023	Bacteria	Surface	149,566,010	1,237,617	825	134,179	75.98	13.82	4.01
TARA023	Protist	DCM	508,610,652	2,707,801	734	336,689	28.23	25.07	7.83
TARA023	Protist	Surface	397,044,232	2,246,571	593	397,140	23.00	25.16	10.31
TARA025	Bacteria	DCM	386,627,816	2,516,865	806	388,546	69.77	14.55	5.35
TARA025	Bacteria	Surface	457,560,422	2,326,838	857	330,773	75.57	10.99	3.18
TARA030	Bacteria	DCM	346,837,034	1,968,945	1097	508,775	80.16	10.31	2.57
TARA030	Bacteria	Surface	478,785,582	1,639,697	1194	204,976	77.70	7.26	2.64
TARA030	Protist	DCM	426,896,616	1,620,343	616	478,892	15.12	17.83	5.13
TARA030	Protist	Surface	430,029,974	1,838,588	628	287,782	22.36	17.60	6.73

*DCM - deep chlorophyll maximum

ªN50 - length of DNA sequence above which 50% of the total is contained

ºrelative abundance - determined using the reads recruited to the contigs ≥2kb in length (data-rich-contigs)

Table 2. Statistics and the number contigs/assemblies at various steps during processing

Contig Grouping	No. of contigs	N50*	Total sequence (bp)
Megahit assemblies 200-499bp	24,999,285	n.d.	9,293,098,676
Megahit assemblies 500-1,999bp	16,103,221	n.d.	13,382,057,993
Megahit assemblies ≥2kb	1,517,360	4,658	6,691,877,664
Megahit assemblies ≥2kb (post-CD-HIT-EST)	1,126,975	4,520	4,894,479,496
Minimus2 contigs	158,414	15,394	1,727,079,865
Minimus2 + unassembled Megahit contigs ≥2kb (data-rich-contigs)	660,937	5,466	3,612,405,904
Minimus2 + unassembled Megahit contigs ≥7.5kb (binned-contigs)	95,506	20,556	1,725,063,313

*N50 - length of DNA sequence above which 50% of the total is contained

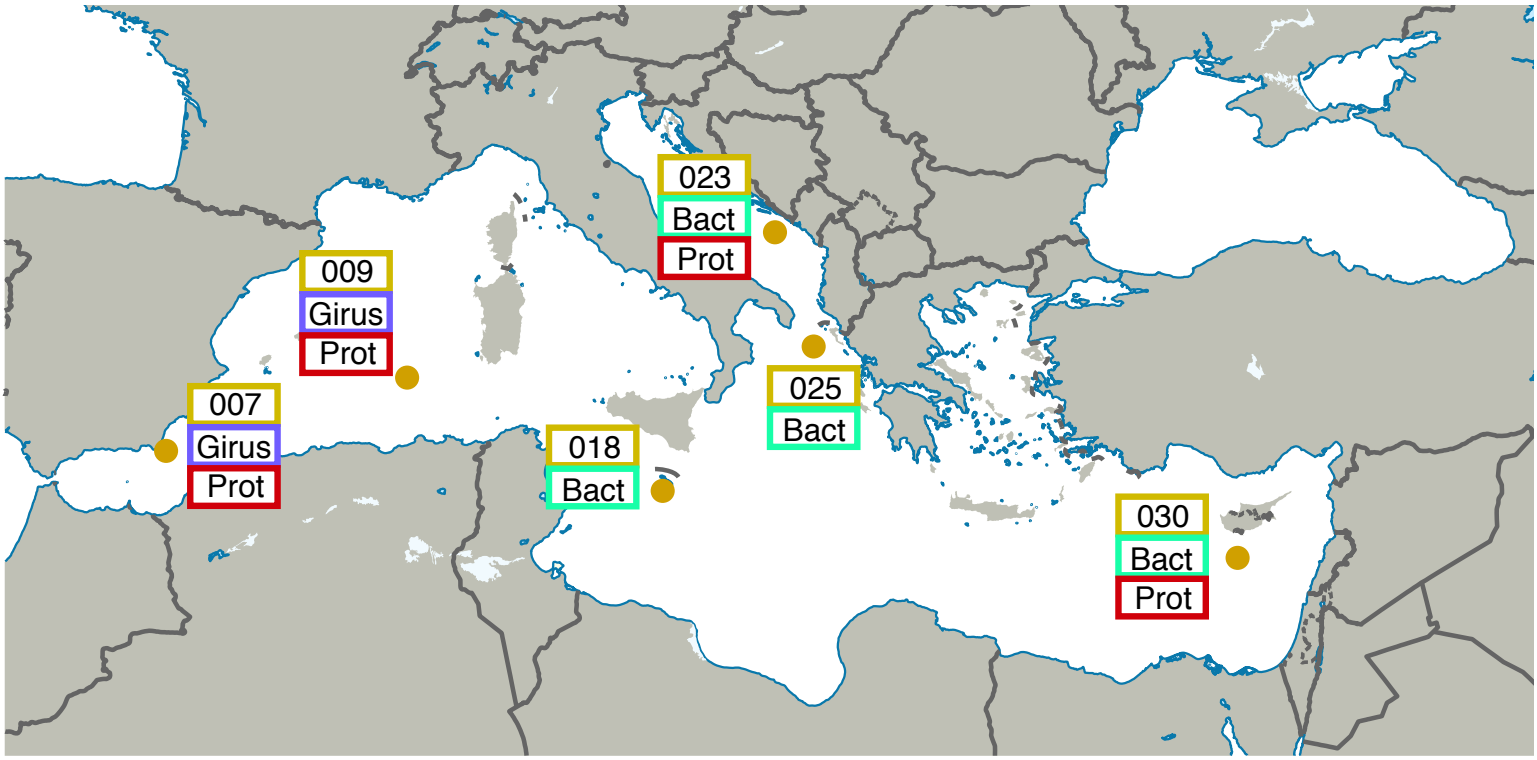


Figure 1. Map illustrating the locations and size fractions sampled for the Tara Oceans Mediterranean Sea datasets. Girus, ‘giant virus’ size fraction (0.22-1.6 µm). Bact, ‘bacteria’ size fraction (0.22-1.6 µm). Prot, ‘protist’ size fraction (0.8-5.0 µm)

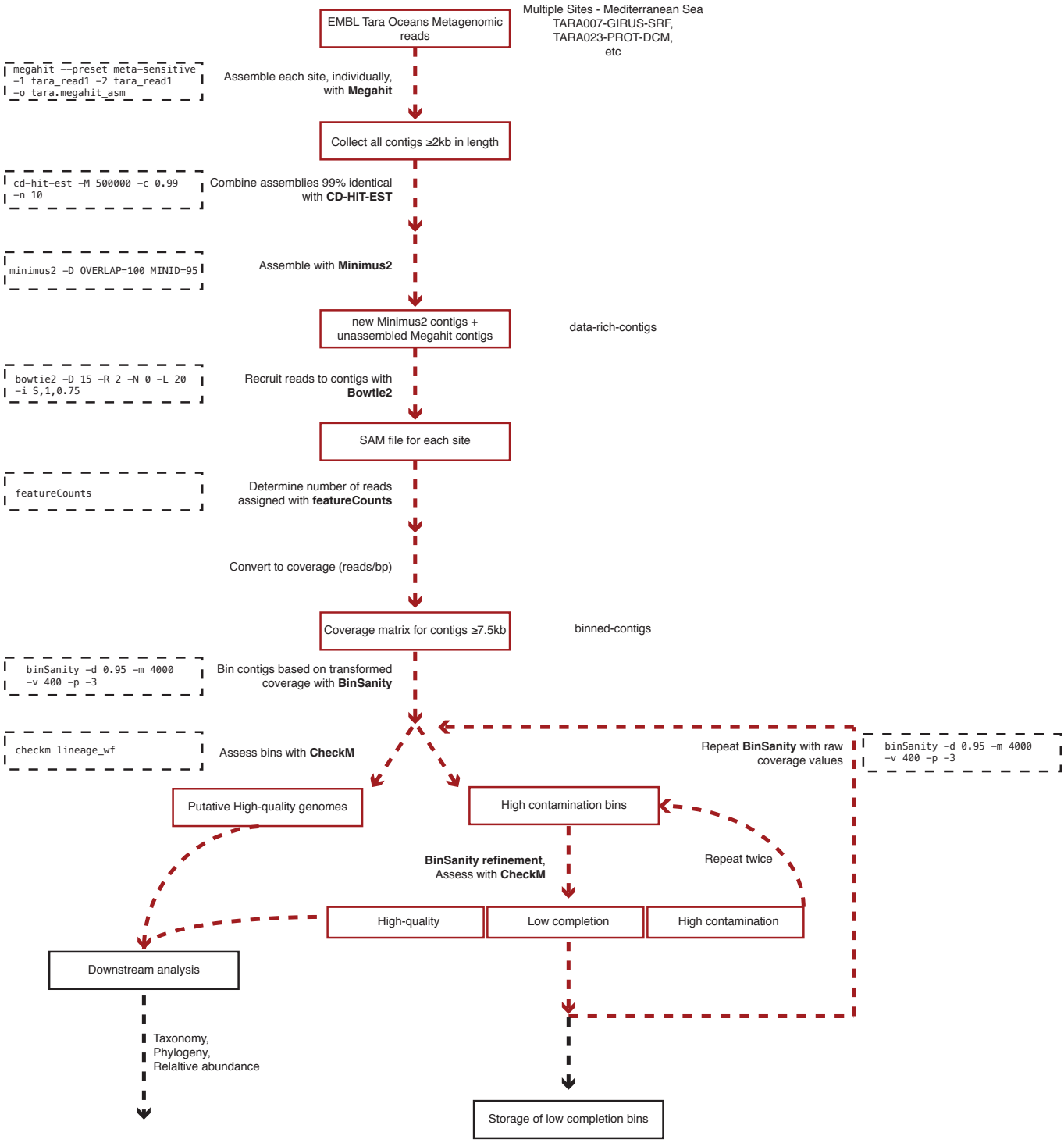
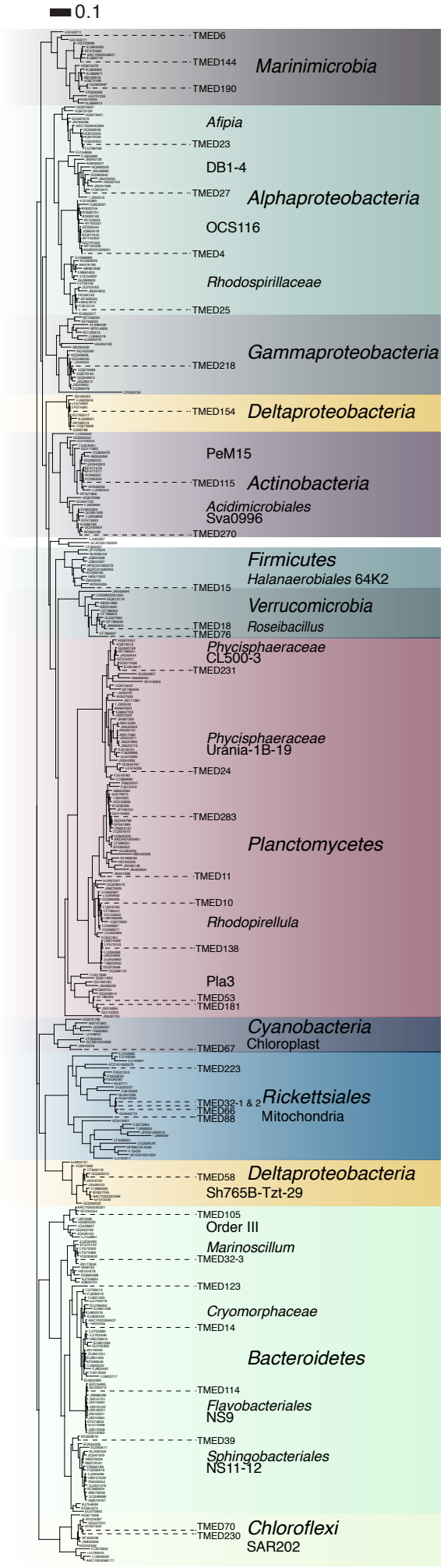


Figure 2. Workflow used to process Tara Oceans Mediterranean Sea metagenomic datasets. Black hash boxes, program or tool used with parameters.

Figure 3. FastTree approximate maximum-likelihood phylogenetic tree constructed with 37 and 785 16S rRNA genes from putative high-quality genomes and references, respectively.



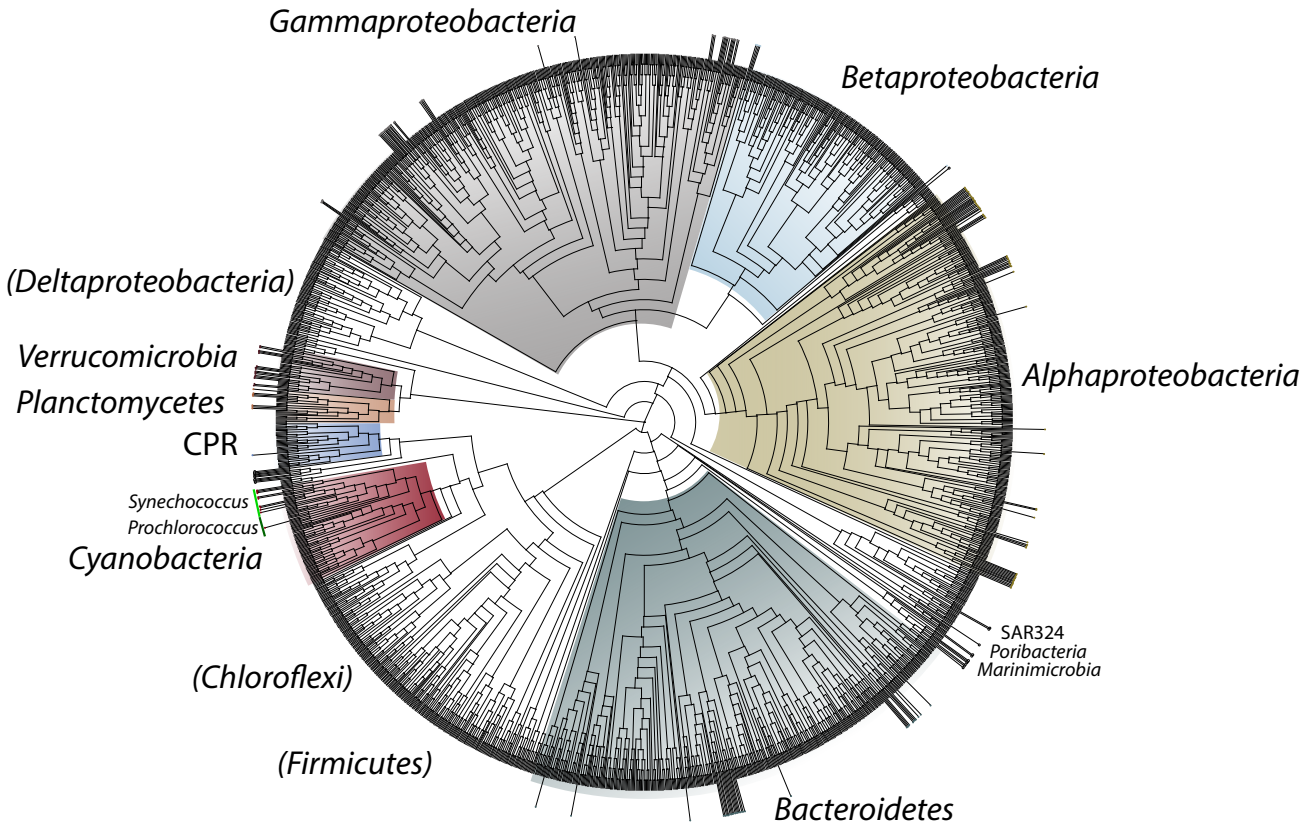


Figure 4. Cladogram of a FastTree approximate maximum-likelihood phylogenetic tree constructed using 16 syntenic, single-copy marker genes for 193 high-quality genomes and 1,729 reference genomes. Leaves denoting the position of the TMED genomes have been indicated by extending beyond the edge of the tree.