

Multiple Syntrophic Interactions in a Terephthalate-Degrading Methanogenic Consortium

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Running title: Metagenomics of a methanogenic consortium

Abstract

Terephthalate (TA) is one of the top 50 chemicals produced worldwide. Its production results in a TA-containing wastewater that is treated by anaerobic processes through a poorly understood methanogenic syntrophy. Using metagenomics, we characterized the methanogenic consortium
5 inside a hyper-mesophilic (i.e., between mesophilic and thermophilic), TA-degrading bioreactor. We identified genes belonging to dominant *Pelotomaculum* species presumably involved in TA degradation through decarboxylation, dearomatization, and modified β -oxidation to H_2/CO_2 and acetate. These intermediates are converted to CH_4/CO_2 by three novel hyper-mesophilic methanogens. Additional secondary syntrophic interactions were predicted in *Thermotogae*,
10 *Syntrophus* and candidate phyla OP5 and WWE1 populations. The OP5 encodes genes capable of anaerobic autotrophic butyrate production and *Thermotogae*, *Syntrophus* and WWE1 have the genetic potential to oxidize butyrate to CO_2/H_2 and acetate. These observations suggest that the TA-degrading consortium consists of additional syntrophic interactions beyond the standard H_2 -producing syntroph – methanogen partnership that may serve to improve community stability.

Introduction

Terephthalate (TA) is used as the raw material for the manufacture of numerous plastic products (e.g., polyethylene terephthalate bottles and textile fibers). During its production, TA-containing wastewater is discharged in large volumes (as high as 300 million m³ per year) and high concentration (up to 20 kg COD m⁻³) (Razo-Flores et al., 2006). This wastewater is generally treated by anaerobic biological processes under mesophilic conditions (~35°C). However, anaerobic processes operated at hyper-mesophilic (46-50°C) and thermophilic (~55°C) temperatures may be preferable due to the ability to achieve higher loading rate (van Lier et al., 1997; Chen et al., 2004), which reduces the reactor volume. Moreover, TA wastewater is usually generated at 54–60 °C, and does not require additional energy input for maintaining reactor temperature (Chen et al., 2004). The microbial biomass usually occurs in the form of granules or biofilms attaching on the surface of porous media. Under such environments, TA degradation has been hypothesized (Kleerebezem et al., 1999) to be based on a syntrophic microbial relationship whereby fermentative H₂-producing bacteria (syntrophs) convert TA via benzoate to acetate and H₂/CO₂, and acetoclastic and hydrogenotrophic methanogens further convert the intermediates to methane by physically positioning themselves close to the syntrophs to overcome the thermodynamic barrier (Stams, 1994; Conrad, 1999; Dolfig, 2001).

In practice the complexities of TA-degrading communities are not as well known. The communities require a long maturation phase (>200-300 days), are difficult to maintain, and do not always result in a successful syntrophic interaction. If the syntrophic interaction is disturbed and the treatment rendered ineffective, the resulting high-concentration effluent must be treated with a more energy-intensive down-stream aerobic biological process. These factors can

significantly increase the operational cost of the process and limit its application on a wider scale.

Several studies have investigated the microbial populations present in methanogenic TA degradation, often using laboratory-scale reactors operated at various temperatures (Kleerebezem
5 et al., 1999; Wu et al., 2001; Chen et al., 2004). Using rRNA-based molecular methods, these studies have found that TA-degrading consortia in bioreactors are dominated by two to three bacterial populations and two types of methanogens (Wu et al., 2001; Chen et al., 2004). The methanogens are relatively straightforward to classify being mainly acetoclastic *Methanosaeta*-related species and a novel hydrogenotrophic methanogenic species in the family
10 *Methanomicrobiales*. The syntrophic bacteria, however, are difficult to identify based on phylogenetic classification, and extremely difficult to obtain in pure culture. In the last decade, only three bacterial species that can degrade TA and its isomers have been successfully co-cultured with methanogens under mesophilic conditions (Qiu et al., 2006; Qiu et al., 2008), and these isolates are different from those found under thermophilic conditions (Chen et al., 2004).
15 This greatly limits the effort to understand the microbial interaction and function in the TA-degrading consortia.

A metagenome analysis was chosen for this study since it has been proven as an effective method for retrieving nearly complete microbial genomes of dominant populations in relatively simple microbial ecosystems (Tyson et al., 2004; Martin et al., 2006). In particular, this study
20 aims to elucidate the microbiology underpinning anaerobic TA-degrading processes, including improved knowledge of the diversity and physiology of participating syntrophs and methanogens, and the mechanism behind the establishment and maintenance of the partnership. This knowledge may lead to the generation of principles which could be applied to establish

different consortia for treating other chemicals discharged from industrial production lines, or to treat contaminants in other environments.

Materials and Methods

5 The anaerobic microbial consortium that degrades terephthalate was selectively enriched using a 1-liter laboratory-scale hybrid bioreactor (Fig. 1a) as described previously (Angelidaki et al., 1990; Chen et al., 2004) (see supplementary text). Biomass was collected from only porous packing filters on Days 221 and 280, and from both filters and sludge bed on Days 346, and 430 for further analyses. These biomass samples were used for genomic DNA extraction, library
10 construction, and sequencing according to standard protocols (http://www.jgi.doe.gov/sequencing/protocols/prots_production.html) (see supplementary text). Detailed metagenome analysis methods are described in the supplementary text. Data can be accessed through the IMG/M (<http://img.jgi.doe.gov/m/>) system.

15 Results and Discussion

Bioreactor operation and performance.

An anaerobic hybrid reactor was successfully operated with TA as the only carbon and energy source for 480 days. This reactor was constructed with an upper section filled with ring-shape porous filters to support the growth of microbial biofilms, and a lower section for the
20 development of anaerobic granular sludge (Fig. 1A). This reactor is unusual and novel in that it was the first methanogenic reactor operated in the hyper-mesophilic temperature zone (46-50°C), whereas previously published studies of TA-degrading communities were at mesophilic (~35°C) or thermophilic (~55°C) temperatures (Kleerebezem et al., 1999; Wu et al., 2001; Chen et al.,

2004). After achieving a good TA removal efficiency (Fig. 1B), sludge samples were taken from the surface of the filter media at Days 221, 280, 346 and 430. Samples were also taken from the sludge bed at Days 346 and 430. These samples taken were used for 16S rRNA and metagenome analysis.

5 *16S rRNA-based community profiling.*

The rarefaction curve analysis indicates that the bacterial population diversity is much higher in terms of OTU number than the archaeal population diversity in any given sample taken from the TA reactor (Supplementary Fig. 1). The phylogenetic distribution of bacterial 16S rRNA clones (Fig. 2) indicates that *Peptococcaceae* (mostly *Pelotomaculum*), *Thermotogae*, *Syntrophaceae*,
10 and candidate phyla OP5 and WWE1 were the dominant bacterial lineages present. Between the biofilm samples (rings 1, 2, 3 and 5) and sludge bed samples (rings 4 and 6) taken, differences in the abundances of major phyla including *Firmicutes*, *Thermotogae*, *Proteobacteria*, and OP5 were observed. These differences are likely attributed to the differences in growth temperature (46°C vs. 50°C) and form (biofilms vs. granules). Archaeal representatives were less diverse and
15 consisted of two major types of methanogens belonging to the orders *Methanomicrobiales* and *Methanosarcinales* (Supplementary Fig. 2). Differences in growth temperature may further explain the variations observed in the microbial populations enriched in previous studies (Supplementary Fig. 3). Using the 16S rRNA gene and McrA gene as biomarkers, temperature-dependent variations were also observed with acetoclastic methanogen populations found in the
20 order *Methanosarcinales* (Supplementary Fig. 4). The hydrogenotrophic methanogens identified here are closely related to methanogens found in mesophilic and thermophilic TA-degrading reactors (Wu et al., 2001; Chen et al., 2004), and together with *Methanolinea tarda* NOBI-1 recently isolated from anaerobic digestion processes (Imachi et al., 2008), form a novel cluster

separate from other known hydrogenotrophic methanogens. The comparison of McrA genes further suggests that the methanogens found in the new cluster are likely different from *M. tarda* NOBI-1 (Supplementary Fig. 4B).

Shotgun sequencing.

5 The assembled sequence data contained 37,818 singlets and 14,526 contiguous fragments of intermediate length (the largest fragment was approximately 240 kb (Supplementary Fig. 5) and 45 fragments between 24-167 kb). Gene prediction on the entire dataset using Genemark resulted in the prediction of 93,104 protein coding genes. A composition-based classifier, PhyloPythia (McHardy et al., 2007), was used to assign those contigs and singlets into major
10 phylogenetic groups (Table 1), including *Pelotomaculum* species, candidate phylum OP5 species, *Methanolinea* species, and *Methanosaeta* species. The highest coverage of an isolate reference genome was observed for *M. thermophila* (~80%) followed by *Pelotomaculum thermopropionicum* (~60%) (Supplementary Fig. 6). However, the *Methanolinea* population appears to be the best covered one as the average read depth is 5.3X with many contigs having
15 10X read depth (Supplementary Fig. 5). In the case of OP5, where a closely related microbial genome was not present in the database, the occurrence was calculated with the phylogenetic marker COGs in the OP5 bin (1.41Mb; G+C content, 28%). Approximately 50% of the OP5 genome is estimated to be covered by the metagenomic data (Table 1).

Pelotomaculum.

20 As a known catabolic degrading organism abundant in the reactor, *Pelotomaculum* is assumed to be largely responsible for catabolic degradation of TA to CO₂, H₂, and acetate. With an average read depth of 3.2X, 1083 contigs were assigned to the *Pelotomaculum* population, comprising 4.3 Mb in total (Table 1). We first searched for genes with known decarboxylase functions that

are responsible for the first decarboxylation step of TA degradation (Supplementary Fig. 7). Two gene sets (tadcc27178-79-80 and tadcc16349) from the *Pelotomaculum* bin were identified to have high sequence similarity and a subunit complement with a known 4-hydroxybenzoate decarboxylase, EC 4.1.1.61, from *Sedimentibacter hydroxybenzoicum* that consists of three subunits (AAD50377, AAY67850, and AAY67851) and belongs to the UbiD family of proteins (Lupa et al., 2005). Two mechanisms have been described for the subsequent fermentation of benzoate to acetate and CO₂: the well known benzoyl-CoA reductase (BCR, EC 1.3.99.15) route used by *Thauera aromatica* (Boll and Fuchs, 1995) and the less understood BCR independent mechanism for reductive dearomatization (Wischgoll et al., 2005). Examining the TA decarboxylase dataset did not show any clear homologs of the *Thauera* benzoyl-CoA reductases. Instead, homologs are found in the alternative BCR independent mechanism within a set of 44 genes that have been postulated to operate in *Geobacter metallireducens* and “*Syntrophus aciditrophicus*” (Butler et al., 2007; McInerney et al., 2007; Peters et al., 2007). The key BCR enzyme in *G. metallireducens* was successfully characterized *in-vitro* (Kung et al., 2009). The metagenome analysis further predicted the pathways that are used for conversion of benzoate to hydroxypimelyl-CoA and subsequent conversion of 3-hydroxypimelyl-CoA via β -oxidation to acetyl-CoA, which in turn gives rise to acetate via substrate-level phosphorylation (Supplementary Fig. 7; Fig. 3). The *Pelotomaculum* bin also contains genes and pathways for the production of butyrate (Supplementary Fig. 7). These observations indicate that TA fermentation by *Pelotomaculum* may lead to the formation of butyrate in addition to acetate. Two genes assigned to *Pelotomaculum* (tadcc25255 and tadcc12813) belong to the Fe-only hydrogenase protein family and are potentially involved in hydrogen generation.

Methanogens.

Three major groups or bins of methanogens belonging to the genera *Methanosaeta* and *Methanolinea* were identified and are known to be syntrophic partners of *Pelotomaculum* (Table 1). Complete pathways for both acetoclastic and hydrogenotrophic methanogenesis were identified (Supplementary Table 1). The first step in acetoclastic methanogenesis is the formation of acetyl-CoA from acetate. It has been proposed (Smith and Ingram-Smith, 2007) that acetoclastic methanogenesis in *Methanosaeta* proceeds with a modified version of the pathway compared to *Methanosarcina*, which utilize the acetate kinase/phosphotransacetylase pathway to convert acetate to acetyl-CoA. In contrast, the *M. thermophila* genome does not include a readily identifiable acetate kinase and it has been proposed that this species utilizes an acetate transporter coupled with acetyl-CoA synthetases to convert acetate to acetyl-CoA (Smith and Ingram-Smith, 2007). Analysis of the TA dataset indicates the presence of acetate transporters (tadcc8417) and acetyl-CoA synthetases, E.C. 6.2.1.1, (tadcc27524, tadcc27520, tadcc27522, tadcc21744, tadcc21743) in the *Methanosaeta* bin. A complete set of the five acetyl-CoA decarbonylase subunits (E.C. 1.2.99.2) was identified as well as genes for the remaining steps of methanogenesis (Supplementary Table 1).

Hydrogenotrophic methanogenesis in the TA community is performed by the *Methanolinea* group. A complete set of Eha hydrogenase enzyme subunits is found in the *Methanolinea* bin. This set is adjacent to formylmethanofuran dehydrogenase which reduces CO₂ to formyl-methanofuran (tadcc39592-39604), suggesting that it may be the enzyme reducing the ferredoxin used by the dehydrogenase (Anderson et al., 2008). In addition, complete sets of *ech* (tadcc3040-tadcc3045) and *mbh* (tadcc17854-tadcc17865) hydrogenases can be found in the *Methanolinea* bin. These hydrogenases are proposed to provide H₂ for the reduction of heterodisulfide (CoM-S-S-CoB) by the heterodisulfide reductase in the absence of

MvhADG hydrogenase (Anderson et al., 2008; Thauer et al., 2008). In this way they link the regeneration of CoM to the reduction of ferredoxin. No homologs to the MvhADG hydrogenase were identified in the *Methanolinea* bin, suggesting that this organism couples ferredoxin and CoB-S-S-CoM reduction to hydrogen (Fig. 4).

5 OP5.

Analysis of the gene content in the OP5 bin (Table 1) revealed the existence of a gene fragment (tadcc9232) related to the *Archaeoglobus* type III RuBisCO. This fragment contains 181 amino acids and exhibits 60% identity to the N-terminus of the large subunit of the *Archaeoglobus* ribulose 1,5-bisphosphate carboxylase raising, EC 4.1.1.39, a link between OP5 and autotrophic
10 CO₂ fixation via the Calvin–Benson–Bassham cycle. Previous work has established that type III RuBisCOs are functional enzymes *in vitro* and also complement RuBisCO deletion in photosynthetic organisms indicating their functionality *in vivo* (Tabita et al., 2007). However, other experiments have shown that type III RuBisCO enzymes are involved in AMP metabolism (Sato et al., 2007). Thus, future experiments are required to validate whether OP5 speices can
15 use type III RuBisCO enzymes for autotrophic CO₂ fixation. Although organisms that contain type III RuBisCOs usually lack recognizable phosphoribulokinases (as is the case for *Archaea*), the OP5 bin contains a gene (tadcc30466) that belongs to the phosphoribulokinase protein family (Pfam domain 00485), which provides the second substrate for the RuBisCO reaction, ribulose 1,5-bisphosphate. These are the two unique enzymatic activities required for CO₂ assimilation.
20 The OP5 bin also contains genes encoding phosphoglycerate kinase, E.C. 2.7.2.3, (tadcc33464), glyceraldehyde-3-phosphate dehydrogenase, E.C. 2.7.1.12, (tadcc33465), and phosphoglycerate mutase, E.C. 5.4.2.1, (tadcc16672) although no representatives of the remaining Calvin–Benson–Bassham cycle genes are readily recognizable in the OP5 bin.

OP5 also contains phosphate butyryltransferase, E.C. 2.3.1.19, (tadcc17546) and two copies of butyrate kinase, E.C. 2.7.2.7, (tadcc17547 and tadcc17544) indicating its ability to produce butyrate and gain energy by substrate level phosphorylation. No acetate kinases or ADP-forming acyl-CoA synthetases were detected in the OP5 genes binned by PhyloPythia.

5 However, inspecting unassigned contigs with GC content lower than 31% identified an acetate kinase (E.C. 2.7.2.1) gene (tadcc15543 on contig taComm3_C5047) that may originate from OP5. Based on these observations, it is proposed that the OP5 populations within the TA community participate in the syntrophic interactions by removing CO₂ and H₂ and producing butyrate and potentially acetate. An operon on contig C11376 binned in OP5 was found to
10 contain a system of Ni-hydrogenases (tadcc33916 and tadcc3391) potentially involved in hydrogen utilization.

Syntrophaceae, Thermotogae, and WWE1.

Syntrophaceae are members of syntrophic communities and are a minor component of the TA-degrading community (Fig 2). To our knowledge, no known *Syntrophaceae* isolates have been
15 reported to degrade TA and most of the isolates utilize propionate, long-chain fatty acids and benzoate. The *Thermotogae* and WWE1 groups were estimated to constitute a significant proportion of the community based on the 16S rRNA analysis. Both for WWE1 and *Thermotogae*, the respective sample populations could not be modeled directly in composition-based binning, due to a lack of sample-specific training data, for WWE1 there was also not
20 sufficient data to directly model the clade (Table 1). A protein-similarity comparison with sequenced members of the phylum *Thermotogae* (utilizing the distribution of BLAST matches for protein-coding genes in the dataset) resulted in 1066 genes with a BLAST matches greater than 60%, with additional 1646 genes having BLAST matches greater than 30%. Among these,

acetate kinase (tadcc6136) (Supplementary Fig. 8) and a phosphotransacetylase (tadcc64919) were identified, suggesting that members of the *Thermotogae* in the TA community may participate in the syntrophic interactions by producing acetate from an intermediate molecule.

This intermediate molecule may be the butyrate produced by the OP5 population. A fragment

5 encoding butyryl-CoA dehydrogenase, E.C. 1.3.99.2, (tadcc28367) further suggests the existence of the butyrate utilizing pathway, and a contig encoding a Fe-only hydrogenase (tadcc1433) suggests the ability of this population to generate H₂. Based on these observations, we hypothesize that the *Thermotogae* species may oxidize butyrate to acetate and H₂.

The sequence similarity-based phylogenetic profiler tool of IMG identified a set of genes

10 from the TA degrading community with high similarity to *Candidatus Cloacamonas acidaminovorans*, that presents the only sequenced bacterial genome of the WWE1 candidate phylum through genome sequence reconstruction and is predicted as a syntrophic bacterium in anaerobic digesters (Pelletier et al., 2008). Comparing the common genes between the TA

community dataset and the *C. acidaminovorans* genome identified 1607 and 3228 genes with

15 sequence identity greater than 80% or 60%, respectively. These genes are likely to originate from the WWE1 population in the TA-degrading community. Among them, acetate kinases (tadcc38857) and acetyl phosphotransferases, E.C. 2.3.1.8, (tadcc25853, tadcc25854) were

identified, suggesting an oxidative pathway generating acetate and energy via substrate-level phosphorylation and Fe-only hydrogenases (tadcc1522, tadcc13376, and tadcc38378), which

20 presumably produce hydrogen. The substrate for this oxidative pathway may be butyrate since members of the butyrate-oxidizing pathway can be identified in the dataset.

Methanogenic syntrophy

Methanogenic syntrophy plays a critical role in the complete degradation of TA to methane (Fig.

4). Thermodynamic considerations suggest a low and narrow-range hydrogen concentration as the essential regulator to establish the syntrophic association between the H₂-producing bacteria and the H₂-consuming methanogens (Schink, 1997; Conrad, 1999). This is because the first

5 reaction from TA to acetate and CO₂/H₂ ($\text{TA} + 8\text{H}_2\text{O} \rightarrow 3 \text{Acetate} + 3\text{H}^+ + 2\text{HCO}_3^- + 3\text{H}_2$, $\Delta G^\circ = 43.2 \text{ kJ/mol}$) can occur only at a low $p\text{H}_2$ (<5 Pa, 1 atm = 101325 Pa) by coupled with methanogenesis ($4\text{TA} + 35 \text{H}_2\text{O} \rightarrow 17\text{HCO}_3^- + 9\text{H}^+ + 15\text{CH}_4$, $\Delta G^\circ < -151.9$) (Schink, 1997).

Also, a minimal threshold $p\text{H}_2$ is required for the H₂-dependent methanogenesis step to produce the minimum amount of energy required for cell maintenance (Conrad, 1999; Dolfing, 2001).

10 When H₂ concentration is higher than this threshold level, H₂-dependent methanogenesis ceases.

Such a low, narrow-range $p\text{H}_2$ is thought to be maintained by “interspecies hydrogen transfer” (Stams, 1994), in which H₂-producing syntrophs and H₂-consuming methanogens cooperate intimately by arranging themselves in close physical proximity in flocs or in a biofilm with short diffusion distances to facilitate hydrogen transfer. TA community metagenomic data revealed a
15 set of hydrogenases, which generate hydrogen in *Pelotomaculum* and consume hydrogen in methanogens.

Using fluorescence *in-situ* hybridization analysis (Supplementary Fig. 9), we observed not only close physical proximity among methanogens and *Pelotomaculum* but also the presence of other microbes (i.e., OP5, WWE1, *Thermotogae*, and *Syntrophus*), as illustrated in Figure 3,
20 associating with syntrophs and methanogens. Metagenomic analysis suggests that these populations can actively participate in the syntrophic interactions to tightly regulate $p\text{H}_2$. OP5 are likely to consume CO₂ and H₂ that are produced by *Pelotomaculum* through the degradation of TA, and produce butyrate. This concept is supported by the ΔG° value (-198.05 KJ/mol) for

the conversion of $\text{CO}_2 + \text{H}_2$ to butyrate ($10\text{H}_2 + 4\text{CO}_2 \rightarrow \text{C}_4\text{H}_8\text{O}_2 + 6\text{H}_2\text{O}$), which is even more favorable under hypermesophilic conditions than mesophilic conditions. OP5 and methanogens can compete for H_2 but the competition is likely to be $p\text{H}_2$ -dependent.

Populations of *Syntrophus*, *Thermotogae*, and WWE1 may be involved in utilizing and recycling butyrate produced by OP5 probably through the secondary β -oxidation pathway. The presence of hydrogenases indicates that both *Thermotogae* and WWE1 gain energy through substrate-level phosphorylation. Although there is no clear evidence for the carbon source that these populations utilize, butyrate (produced by OP5) may serve as a key carbon source. This would suggest that, like *Syntrophus*, some members of *Thermotogae* and WWE1 are possibly syntrophs. However, they are not persistently dominant populations and their abundance varies throughout the reactor operation (Fig. 2). TA metagenomics data indicates the presence of butyrate kinases and phosphotransacetylases in the *Pelotomaculum* bin, suggesting that this population may ferment TA not only to acetate but also butyrate. Our previous study also observed a detectable level of butyrate by using 2-bromoethanesulfonate to inhibit the methanogenesis step in a mesophilic TA-degrading consortium (Wu et al., 2001). It is possible that this type of fermentation results in the production of a second end product (butyrate in addition to acetate) and triggers a secondary syntrophic interaction involving butyrate-oxidizing organisms.

Several studies (Chan, 2000; Qiu et al., 2006; Imachi et al., 2008) have observed the existence of multiple bacterial populations in highly enriched methanogenic cultures degrading carbon substrates like formate, acetate, propionate and phthalate isomers. These observations were demonstrated through a defined mixed culture (Dolfing et al., 2008), suggesting that syntrophic interactions in methanogenic enrichments are more complex than simple pairwise

syntroph-methanogen relationships. Rather, they include other members that maintain and regulate the interspecies hydrogen transfer, which is the cornerstone of syntrophy. In conclusion, our overall observations imply that degradation of organic carbon is not simply a syntrophic interaction between H₂-producing syntrophs and methanogenic archaea. They further support the hypothesis that additional secondary interactions take place in order to maintain the stability of the TA degrading community.

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Table 1. Phylogenetic affiliations of major bins in the TA dataset identified with the composition-based classifier, PhyloPythia (McHardy et al., 2007) ^{*}.

Phylogenetic affiliation	No of DNA contigs	Total sequence (Mb)	Average read depth	Expected genome size (Mb) ^{**}
<i>Bacteroidetes</i> (class)	70	0.155	2.3±1.1	-
<i>Bacteroidales</i>	120	0.235	2.2±0.9	-
<i>Betaproteobacteria</i>	73	0.096	1.7±0.6	-
<i>Deltaproteobacteria</i>	160	0.343	2.1±0.8	-
Uncultured <i>Syntrophus</i>	196	0.724	2.9±1.3	1.9
<i>Geobacter</i>	264	0.578	2.1±0.7	-
<i>Firmicutes</i>	430	0.628	2.1±0.7	-
<i>Clostridia</i>	66	0.372	3.3±1.6	-
Uncultured <i>Pelotomaculum</i> spp [#]	1083	4.256	3.2±1.5	3.6
OP5	228	1.411	3.8±1.9	2.8
<i>Spirochaetes</i> (class)	81	0.177	2.3±0.9	-
<i>Euryarchaeota</i>	1560	2.648	2.1±0.9	-
<i>Thermoplasmata</i>	71	0.148	1.9±0.8	-
<i>Methanomicrobiales</i>	36	0.098	2.4±1.8	-
Uncultured <i>Methanolinea</i> spp [#]	78	2.162	5.3±3.9	3.7
<i>Methanosarcinales</i>	15	0.095	3.7±1.9	-
Uncultured <i>Methanosaeta</i>	1180	2.613	2.6±1.1	3.1
Uncultured <i>Methanosaeta</i>	351	2.361	4.2±1.3	2.8

* No DNA contigs were binned to WWE1 related to *C. acidaminovorans* due to insufficient training data for PhyloPythia. 16S rRNA clone library indicated that 132 sequences were affiliated with WWE1 and grouped into two different clusters. One of the clusters (37/132) was closely related to *C. acidaminovorans* (similarity = 96-98.8%).

5 ** Expected genome size was calculated based on the percent coverage of the corresponding isolate genomes. For example, there are 1735 genes in *Pelotomaculum thermopropionicum* that are best-BLAST matches to genes from the metagenome dataset. Given that *P.*

thermopropionicum contains 2920 genes, we estimate the genome size of the uncultured *Pelotomaculum* sp. was 7.16 Mb ($4.256 \times 2920 / 1735$). However, there are at least two strains of

10 *Pelotomaculum* present in the sample. Therefore, the individual genome size for each strain is estimated to be around 3.6 Mb. For estimating the *Methanolinea* genome size we used as a reference genome *Methanoculleus marisnigri*. For *Methanosaeta* genome size, 2.6 Mb of sequences give hits to 1438 proteins in *M. thermophila* genome has 1730 CDS predicted so the expected genome size would be $(2.6 \times 1730) / 1438 = 3.1$ Mb. In the case of OP5, expected genome

15 size was calculated based on the occurrence of phylogenetic marker COGs that are defined as COGs having one or mostly one member in the genomes that are present and are available in IMG/M. The OP5 bin contained 91 out of 180 phylogenetic marker COGs.

#, At least two species/strains were observed in each bin. With SNP frequencies of at least 0.03% to 0.07% (data not shown), we concluded that these species/strains are not clonal.

Figure legends

Fig. 1. Terephthalate (TA)-degrading laboratory-scale anaerobic hybrid bioreactor. **(A)**

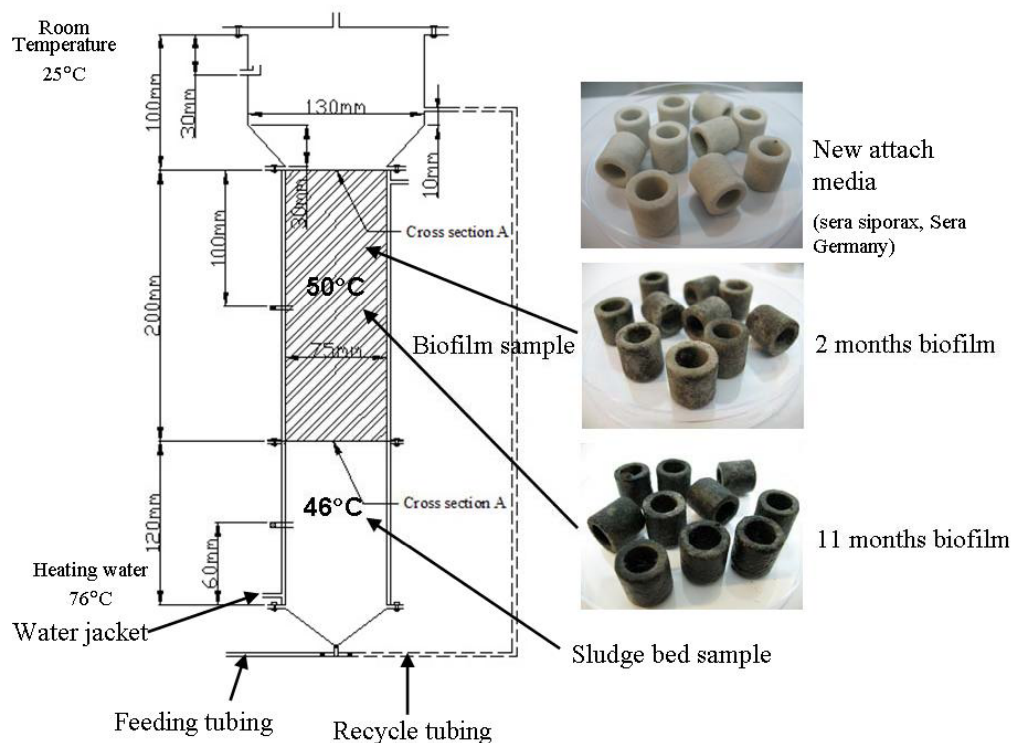
Schematic of the laboratory-scale anaerobic terephthalate-degrading hybrid reactor operated with a temperature gradient from ~ 46°C at the bottom to 50°C in the upper zone. Inserts illustrate

5 freshly grown biofilm biomass on the surface of the media after two and 11 months of enrichment; and **(B)** Performance of the reactor over 480-day operation. Under the initial operational conditions (i.e., TA-loading rate of 0.70-0.78 gTA/d.l, and hydraulic retention time (HRT) of 4 days), TA removal efficiency was gradually improved to 72.7% by day 124. By shortening the HRT (3 d on Day 127, 2 d on Day 168 and then to 1.5 d on Day 182) and
10 increasing the TA loading concentration (to 3.2 g on Day 364), the TA loading rate was increased to 2.13 gTA/d.l by Day 364. Concurrently, the TA removal efficiency increased over the operation period reaching a 99% removal efficiency by Day 308. During the entire operation no sulfate reduction activity was detected. Samples were removed at the indicated time points (arrows) and the genomic DNA was extracted for 16S rRNA clone library construction and
15 metagenomics analysis.

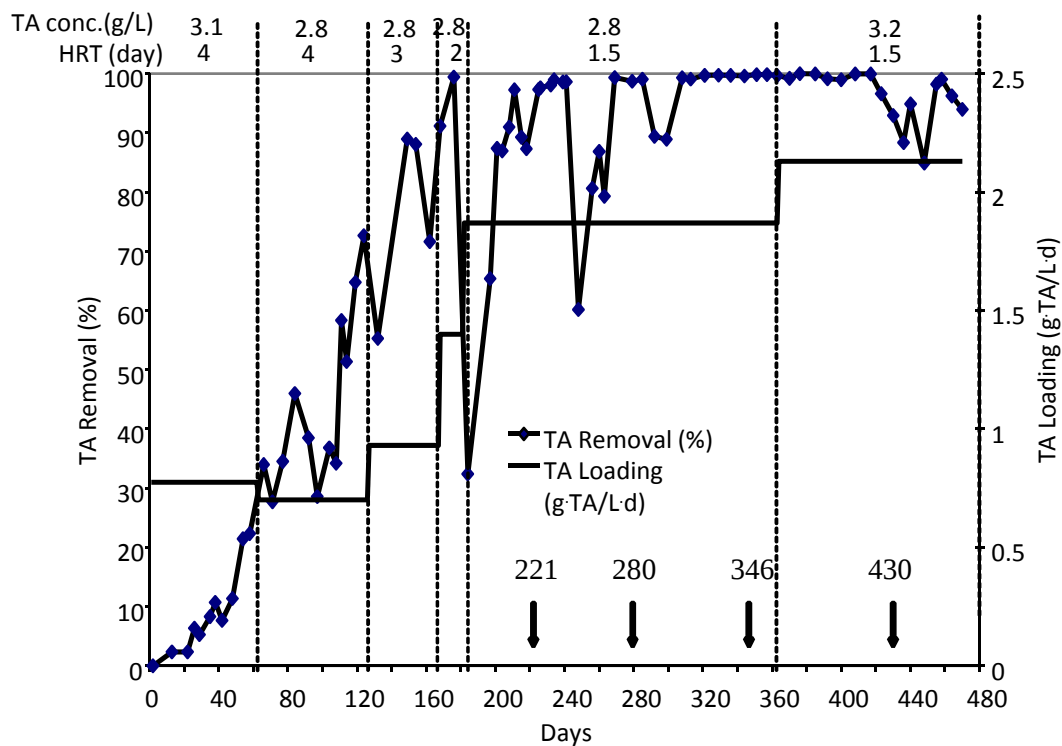
Fig. 2. Bacterial population dynamics of the TA-degrading bioreactor as revealed by 16S rRNA clone library. Samples (number of 16S rRNA sequences) from inner to outer of the ring chart were Day 221 biofilms (287), Day 280 biofilms (254), Day 346 biofilms (337), Day 346 sludge bed (289), Day 430 biofilms (352), and Day 430 sludge bed (287).

20 **Fig. 3.** Metabolic reconstruction of the TA-degrading syntrophic community. The metagenomic data revealed pathways for the degradation of the aromatic (terephthalate) compound, the recycling of the intermediates (H₂/CO₂, acetate, and butyrate) and the subsequent syntrophic methanogenesis.

(A)



(B)



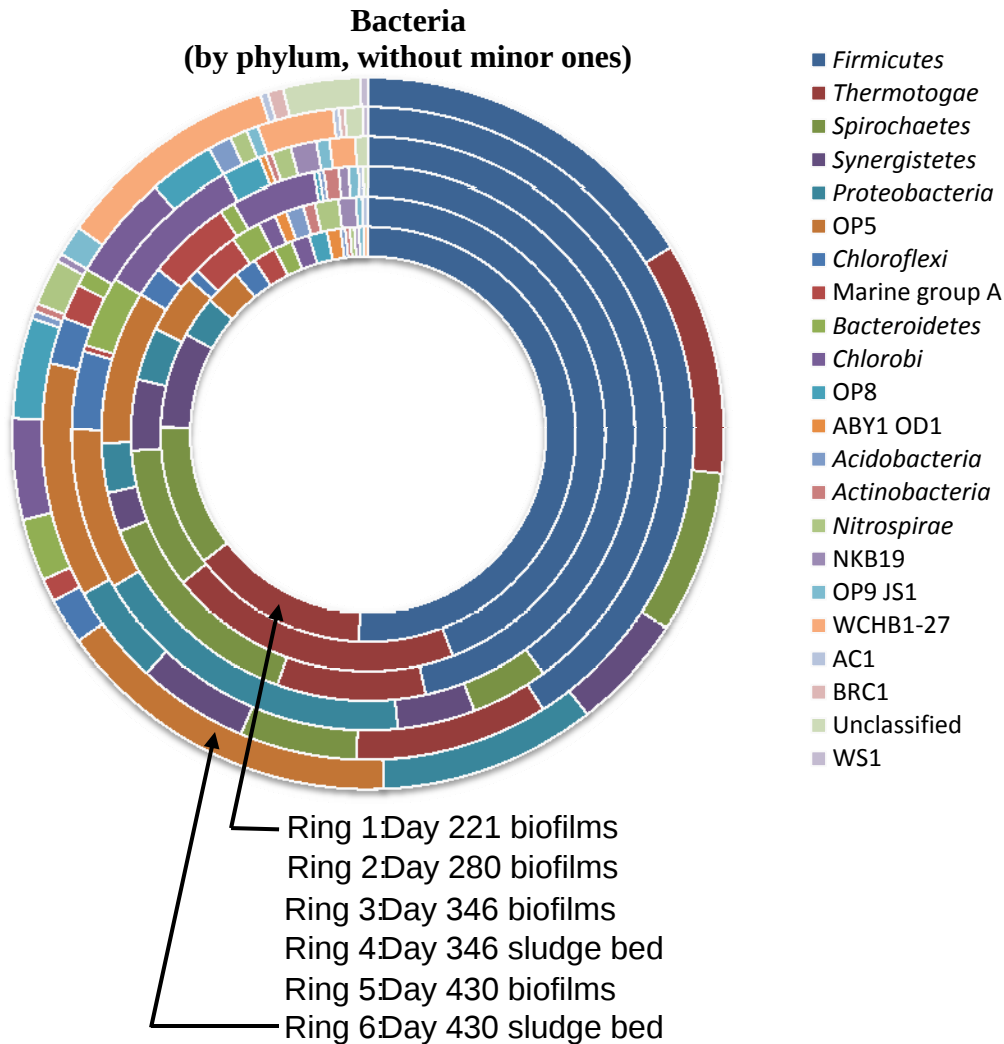
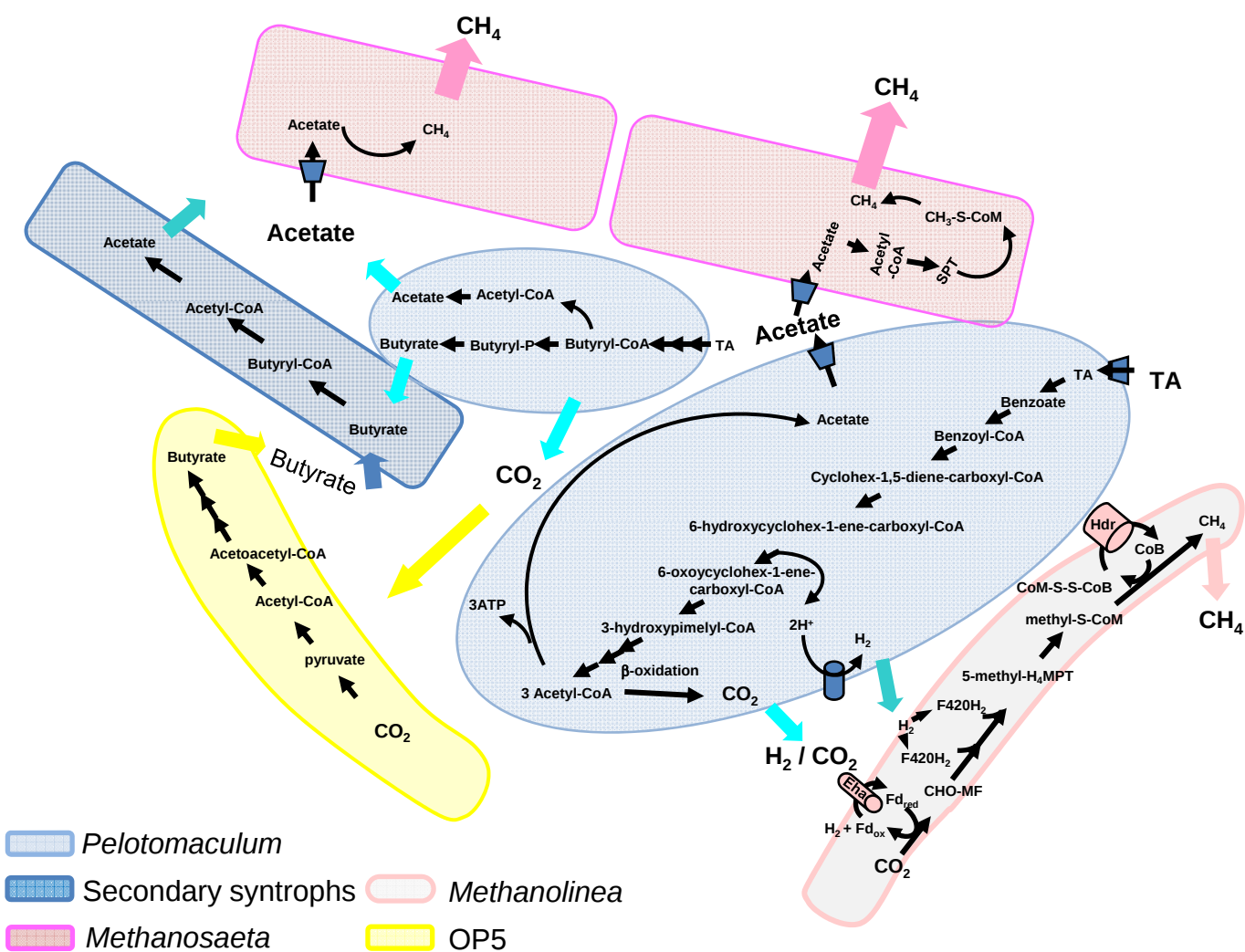


Fig. 2. Bacterial population dynamics of the TA-degrading bioreactor as revealed by 16S rRNA clone library. Samples (number of 16S rRNA sequences) from inner to outer of the ring chart were Day 221 biofilms (287), Day 280 biofilms (254), Day 346 biofilms (337), Day 346 sludge bed (289), Day 430 biofilms (352), and Day 430 sludge bed (287).



Supplementary Figure Legend

Fig. 1. The rarefaction curve generated for the bacterial populations and archaeal populations in those six samples taken from the TA reactor. Sequence dissimilarities of 3 and 5% were both used to produce the rarefaction curves of the domain *Bacteria* and domain *Archaea*. Higher microbial diversity was observed with the domain *Bacteria* than the domain *Archaea* in any given sample taken from the TA reactor. Within the domain *Archaea*, all samples had a similar rarefaction curve except for the sample taken at day 430 from the sludge bed.

Fig. 2 Archaeal population dynamics of the TA-degrading bioreactor as revealed by 16S rRNA clone library. Samples (number of 16S rRNA sequences) from inner to outer of the ring chart were Day 221 biofilms (359), Day 280 biofilms (362), Day 346 biofilms (343), Day 346 sludge bed (356), Day 430 biofilms (278), and Day 430 sludge bed (211).

Fig. 3 16S rRNA neighbor joining phylogeny tree of *Pelotomaculum* species from the family *Desulfotomaculum* (number of bootstrapping, 500). The dominant bacterial 16S rRNA sequences obtained from hypermesophilic and thermophilic TA-degrading bioreactors were shown. The *Pelotomaculum*-related sequences obtained under hyper-mesophilic conditions (46-50°C) are different from those *Pelotomaculum*-related syntrophs obtained under thermophilic conditions (~55°C).

Fig. 4 Methanogen diversity in TA-degrading reactor as determined by 16S rRNA and McrA. (A) 16S rRNA neighbor joining phylogeny tree (number of bootstrapping, 500). Within the *Methanosarcinales*, the methanogen sequences obtained from mesophilic and thermophilic TA-

degrading consortia were closely related to *Methanosaeta concilii* and *Methanosaeta thermophila*, respectively. However the methanogen sequences obtained from the hypermesophilic TA-degrading consortium formed two novel clusters, suggesting these methanogens are different from those predominating in mesophilic and thermophilic conditions. Within the order *Methanomicrobiales*, the methanogen sequences obtained from mesophilic, hypermesophilic and thermophilic TA-degrading consortia were all clustered with a novel methanogen, *Methanolinea tarda*, recently isolated from a propionate-degrading anaerobic reactor. *M. tarda* is a hydrogen-utilizing methanogen. (B) McrA-based neighbor joining phylogeny tree (bootstrap = 500). Sequences obtained from the TA metagenomics were denoted with 'tadcc'. tadcc5364 and tadcc11668 likely represented one or two different clusters within the genus *Methanosaeta* and are different from *Methanosaeta thermophila* primarily found in thermophilic conditions (~55°C). Likewise, tadcc40165 and tadcc3600 represented a cluster that is different from the cluster containing tadcc70096 and *M. tarda* within the *Methanomicrobiales*.

Fig. 5 Size distribution and read depth of DNA contigs obtained by shotgun sequencing and assembly. In total, 52342 DNA contigs were obtained. The largest contig is approximately 240 kb in size and contains 271 genes. Additional 45 fragments are 24 to 167 kb long.

Fig. 6 Genome coverage of sequenced isolate bacterial and archaeal genomes. Genome coverage is calculated based on the distribution of best BLAST matches of protein-coding genes in the metagenome dataset as described in the supplementary text.

Fig. 7 Reconstruction of the TA degradation pathway operating in *Pelotomaculum* sp. All genes necessary for terephthalate degradation have been identified in the *Pelotomaculum* bin. To identify specific TA decarboxylases, searches for genes with known decarboxylase functions revealed two gene sets (tadcc27178-79-80 and tadcc16349) that have sequence similarity and a

subunit complement with a known 4-hydroxybenzoate decarboxylase (EC 4.1.1.61) from *Clostridium hydroxybenzoicum* (1). This decarboxylase consists of three subunits and belongs to the UbiD family of proteins. Only one of these genes, tadcc16349, resides on a contig assigned to the *Pelotomaculum* bin. The contig containing the tadcc27178 gene set (taComm3_C8975) is binned to a higher-level classification of *Clostridia*, but contains two genes with a high degree of similarity to *Pelotomaculum* genes (a dnaE gene (tadcc27166) and an endonuclease (tadcc27168)), and includes three fosmid end-reads whose mate pairs map to contigs in the *Pelotomaculum* bin. Thus we conclude that the tadcc27178 gene set likely derives from a *Pelotomaculum* population. All genes necessary for terephthalate degradation have been identified in the *Pelotomaculum* bin except the phosphotransacetylase gene. Multiple phosphate butyryltransferases (tadcc9380, tadcc37666, tadcc28170) and butyrate kinases, EC 2.7.2.7, (tadcc9381, tadcc37665, tadcc28171) are present in the *Pelotomaculum* dataset.

Fig. 8 Protein neighbor joining phylogenetic tree of acetate (Ack) and butyrate kinases (Btk) (number of bootstrapping, 500). Locus tags correspond to the genes from the following organisms: CPR, *Clostridium perfringens* SM101; CPE, *Clostridium perfringens* 13; CTC, *Clostridium tetani* E88; CAC, *Clostridium acetobutylicum* ATCC 824; CD, *Clostridium difficile* 630; Amet, *Alkaliphilus metalliredigens* QYMF; TTE, *Thermoanaerobacter tengcongensis* MB4; Gmet, *Geobacter metallireducens* GS-15; Geob, *Geobacter* sp. FRC-32; TRQ2, *Thermotoga* sp. RQ2; TM, *Thermotoga maritima* MSB8; CTN, *Thermotoga neapolitana* DSM 4359; Tmel, *Thermosipho melanesiensis* BI429; THA, *Thermosipho africanus* TCF52B; TLET, *Thermotoga lettingae* TMO; Hore, *Halothermothrix orenii* H 168; BLI, *Bacillus licheniformis* ATCC 14580; GK, *Geobacillus kaustophilus* HTA426; Bcer98, *Bacillus cereus*; BT9727,

Bacillus thuringiensis; CAO, *Candidatus* Cloacamonas acidaminovorans; Cbei, *Clostridium beijerinckii* NCIMB 8052.

Fig. 9 Biofilm samples of TA-degrading methanogenic consortium as revealed by FISH. (A) The *Desulfotomaculum*-related cells (yellow color) as targeted by probe lh820 accounted for 85.2 ± 6.4 % of the total bacterial populations detected by probe EUB338mix (in Green). (B) Bacterial and archaeal cells targeted by probes EUBmix (green color) and ARC915 (red color), respectively, appeared in equal abundance in the biofilm sample. Size bar = 10 μ m.

Fig. S1

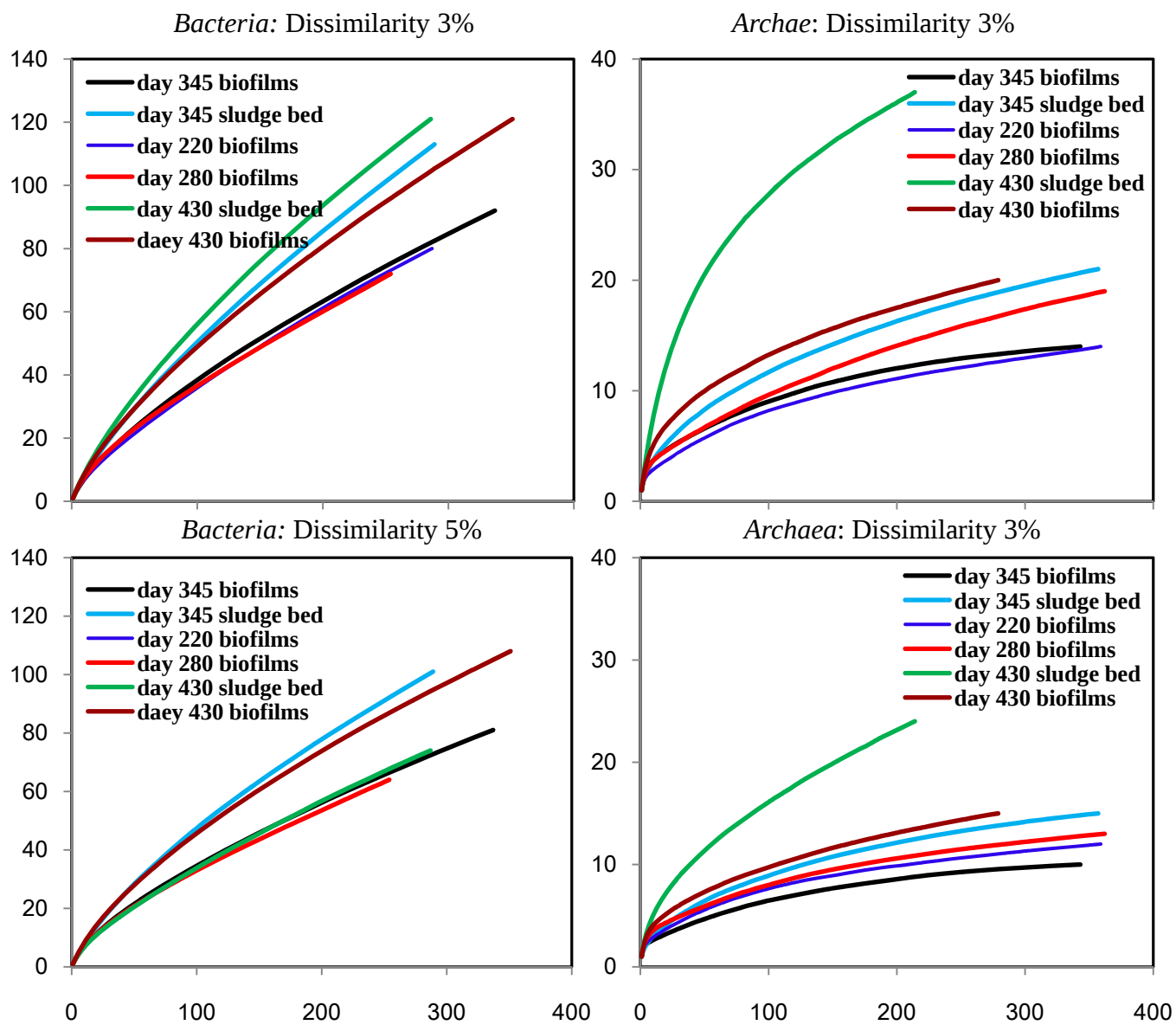


Fig. S2

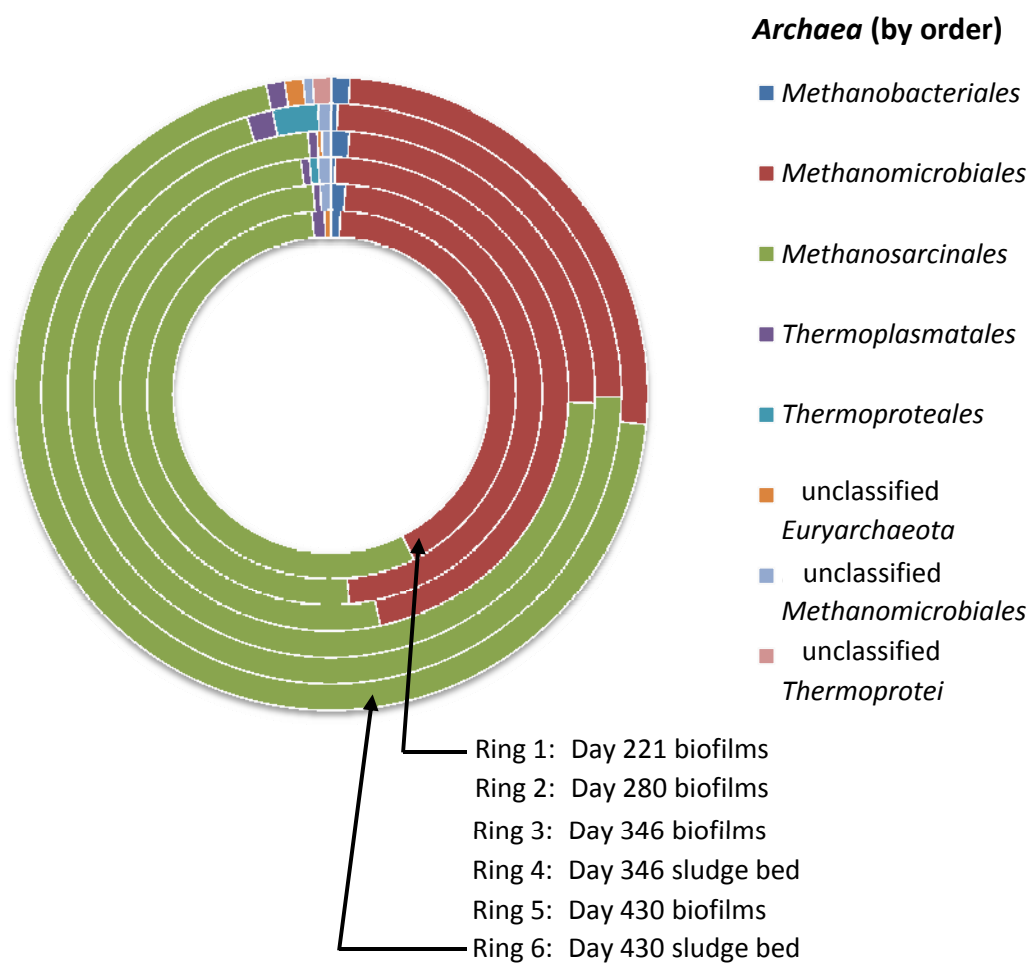


Fig. S3

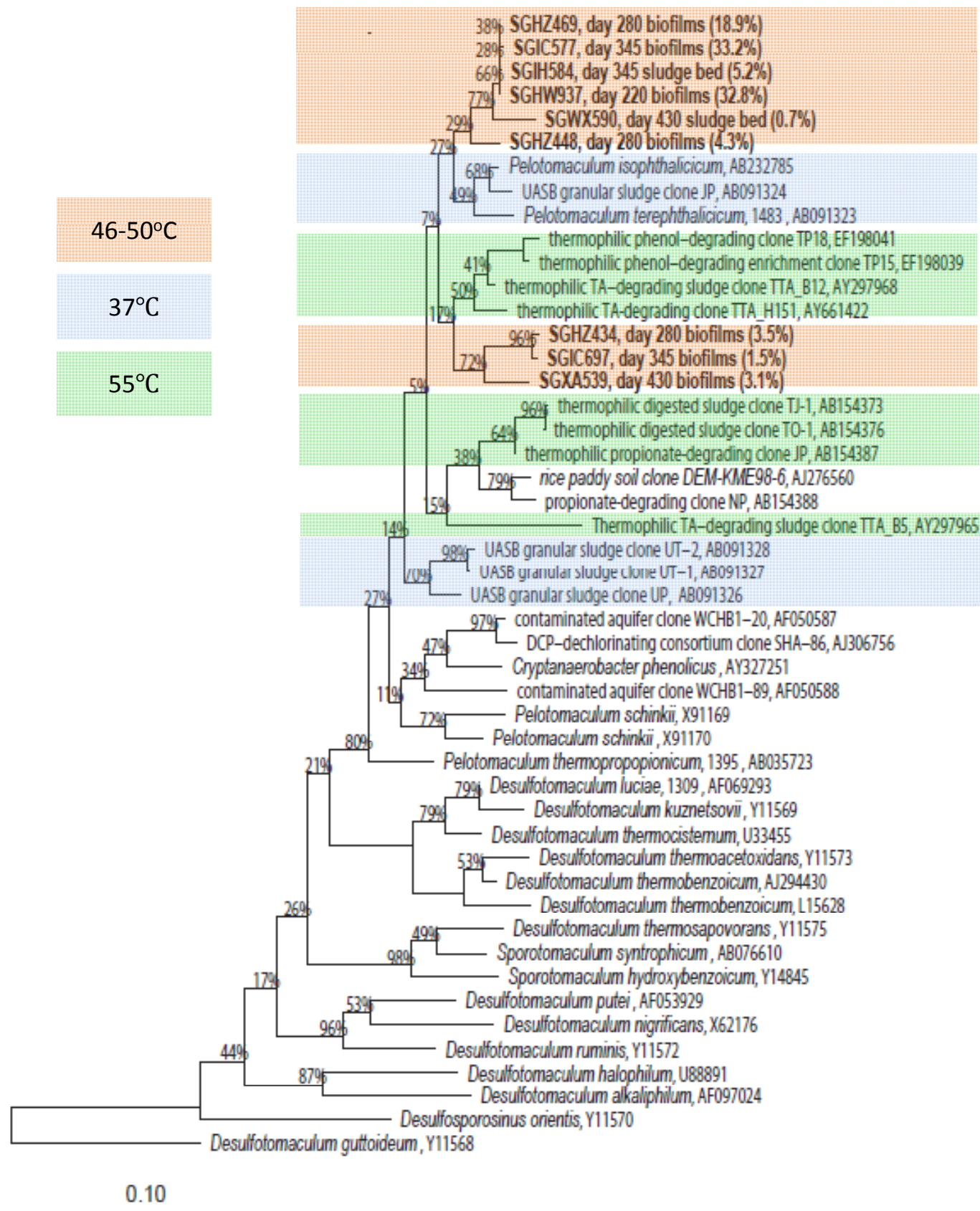


Fig. S4 (A)

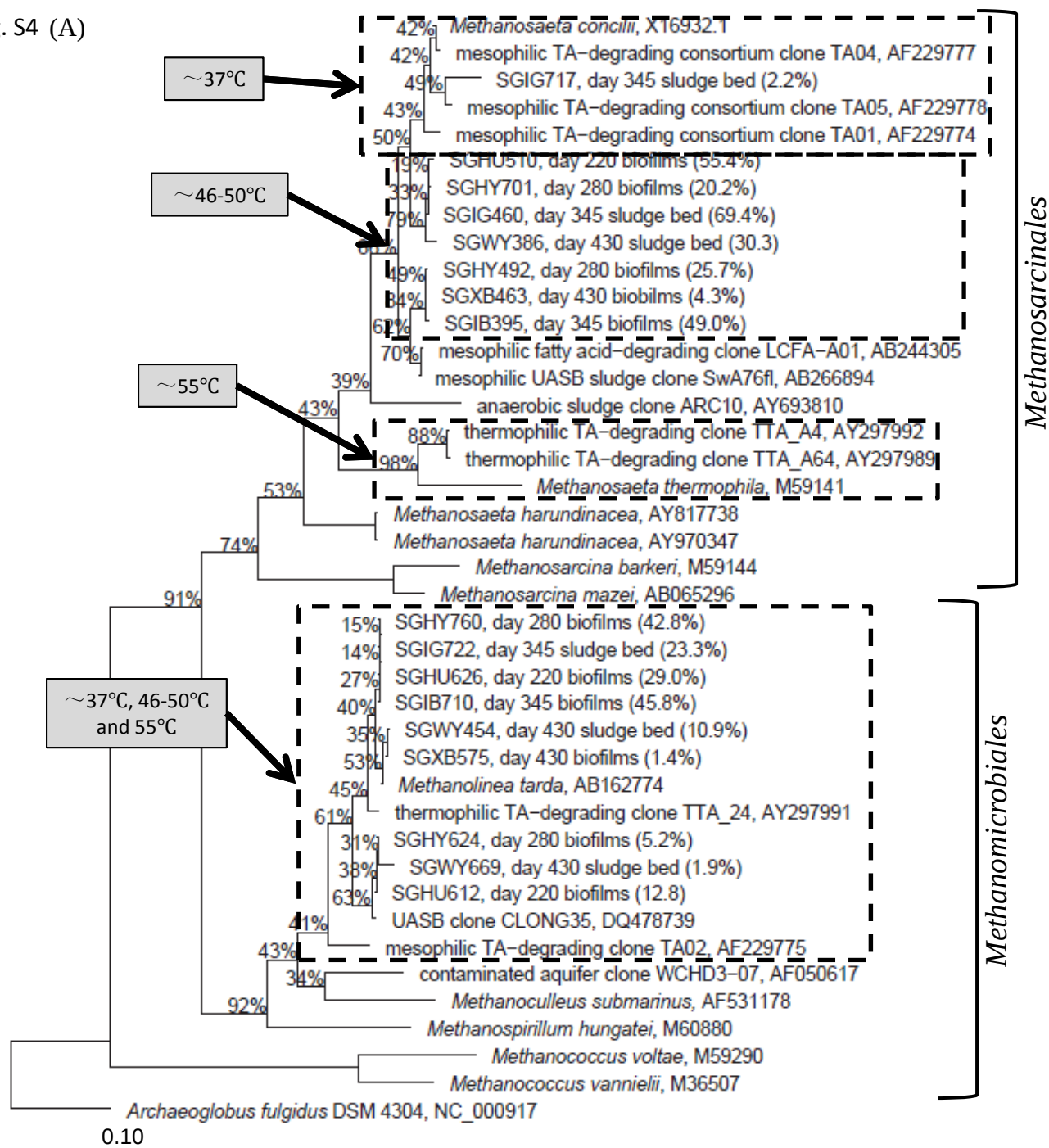


Fig. S4 (B)

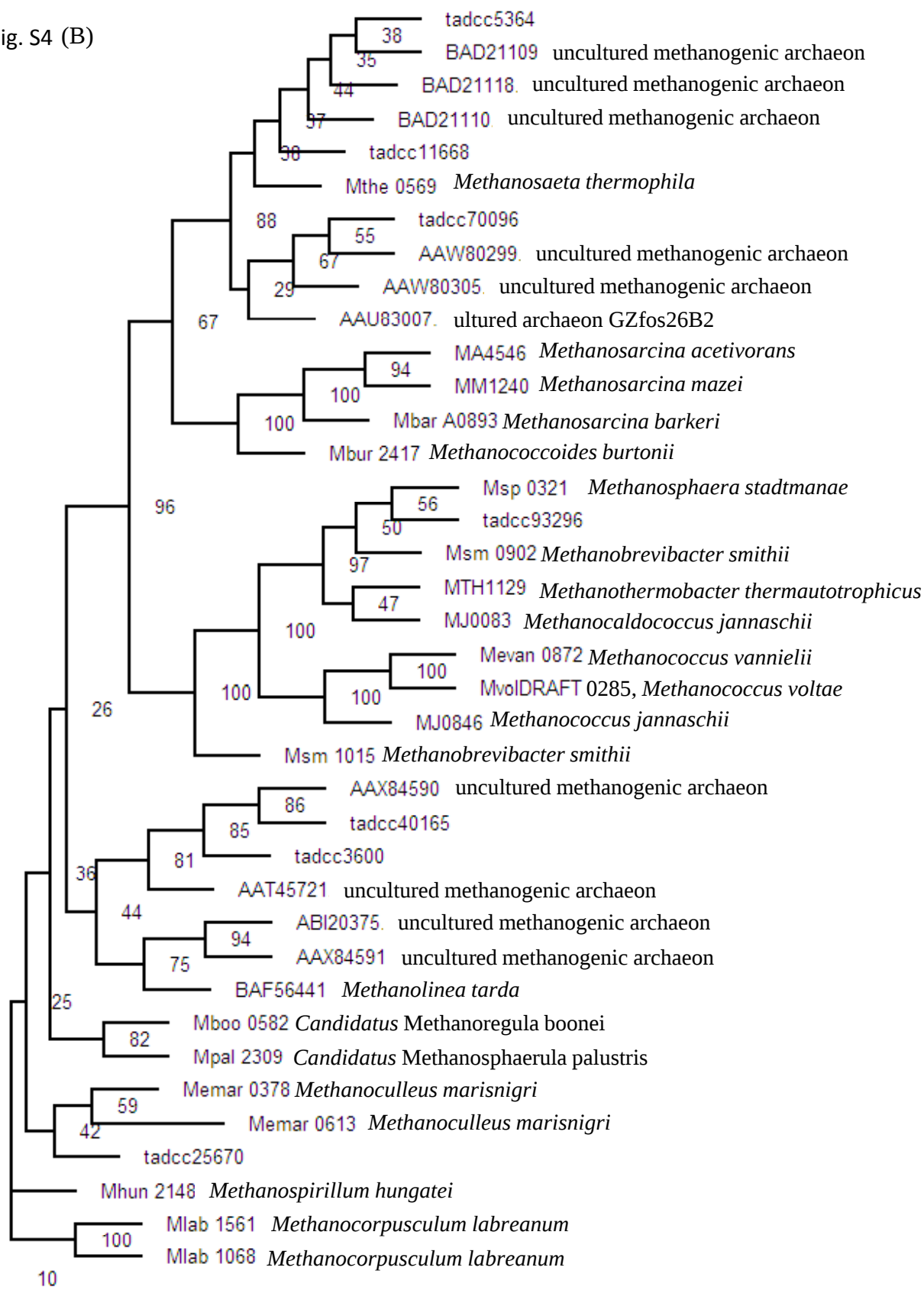


Fig. S5

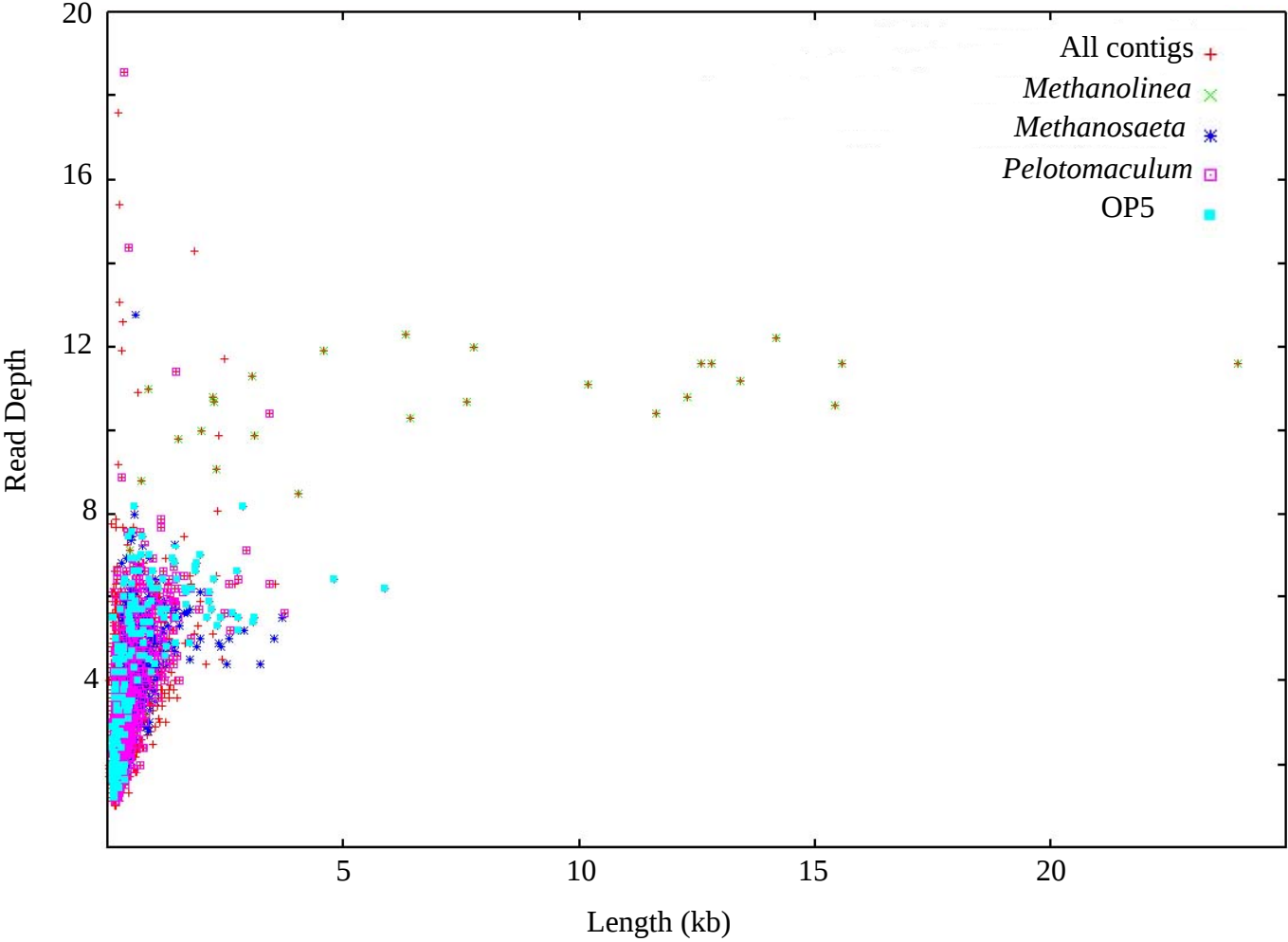


Fig. S6

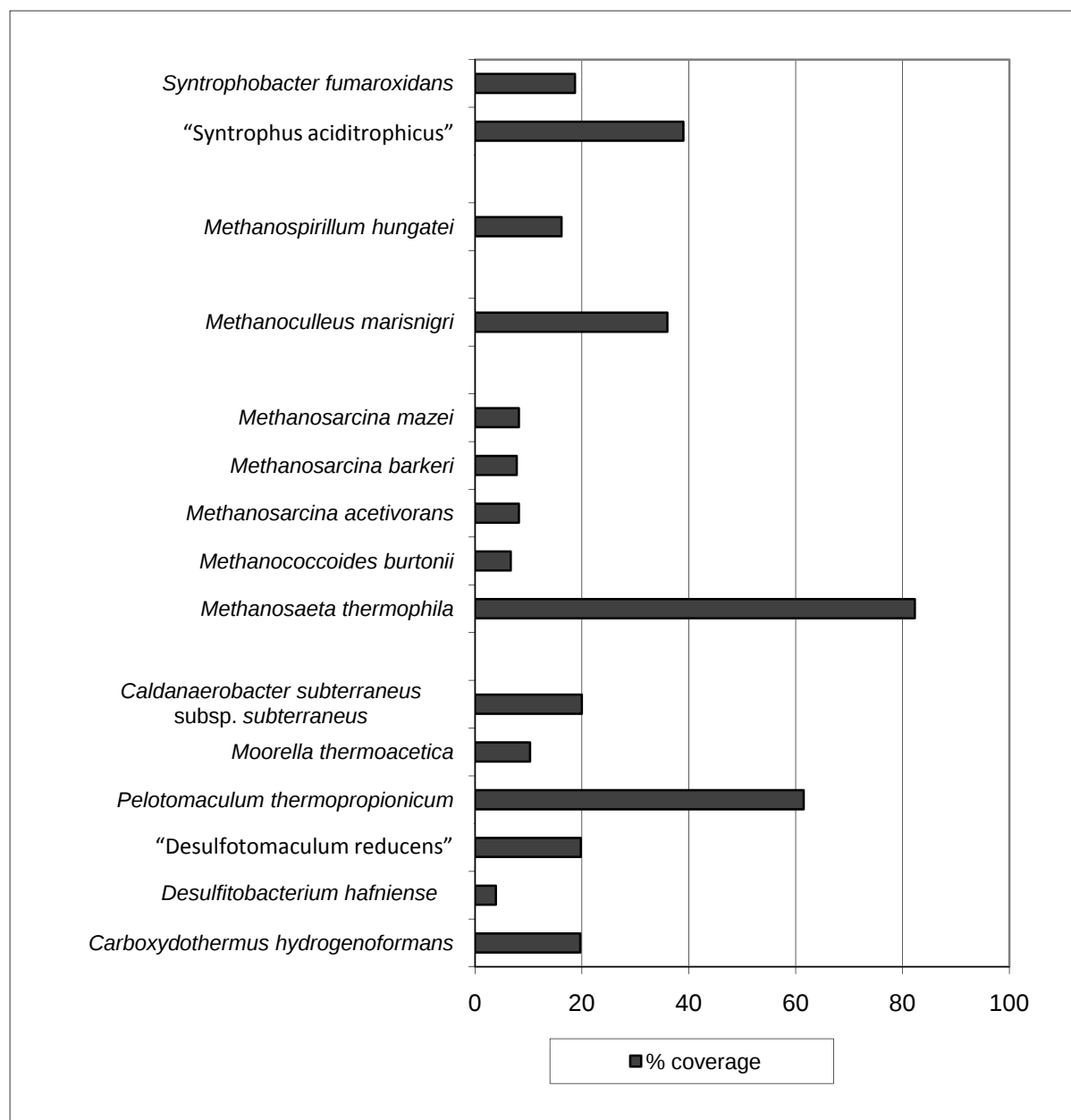


Fig. S7

Pelotomaculum sp.

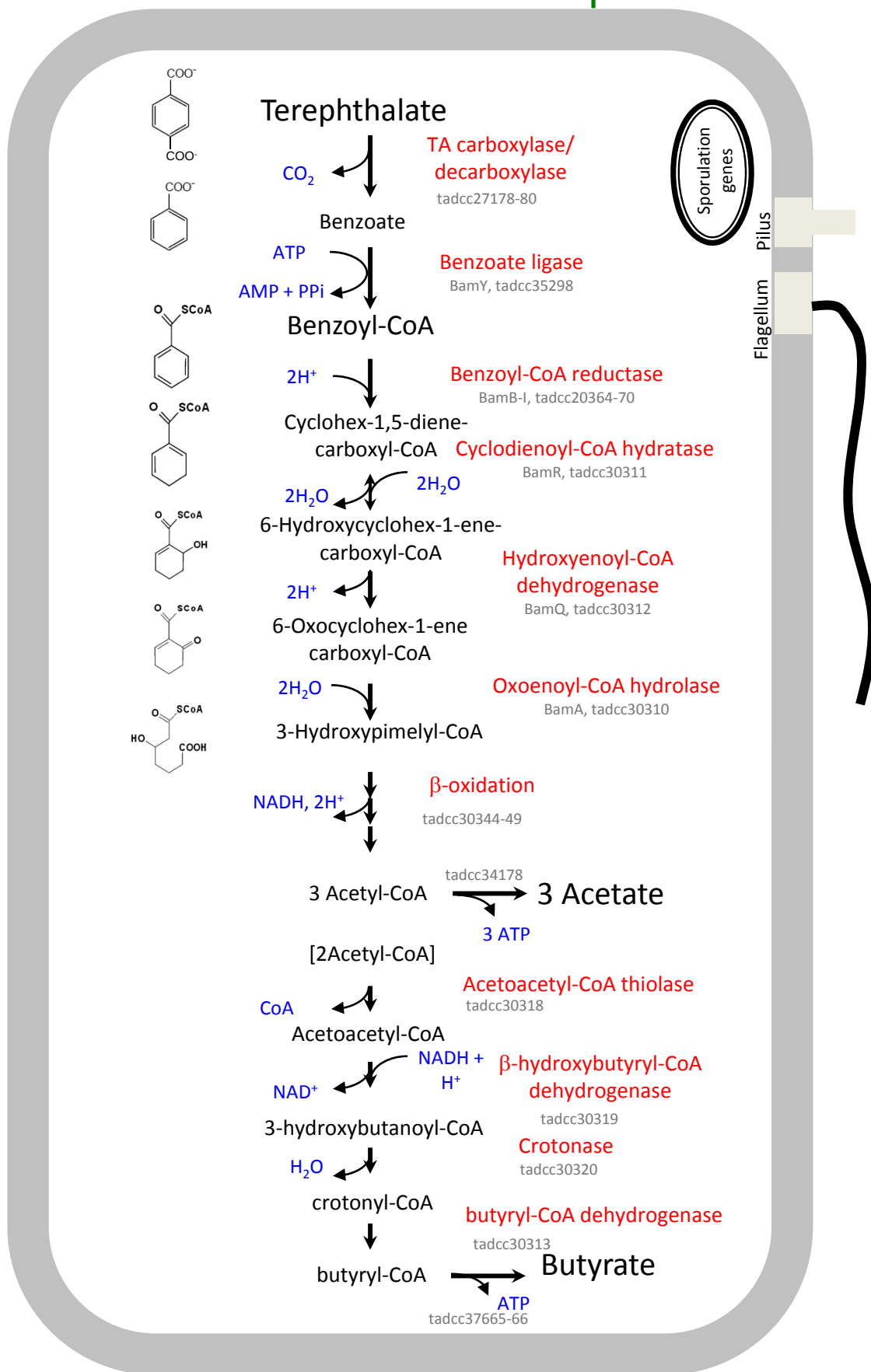


Fig. S8

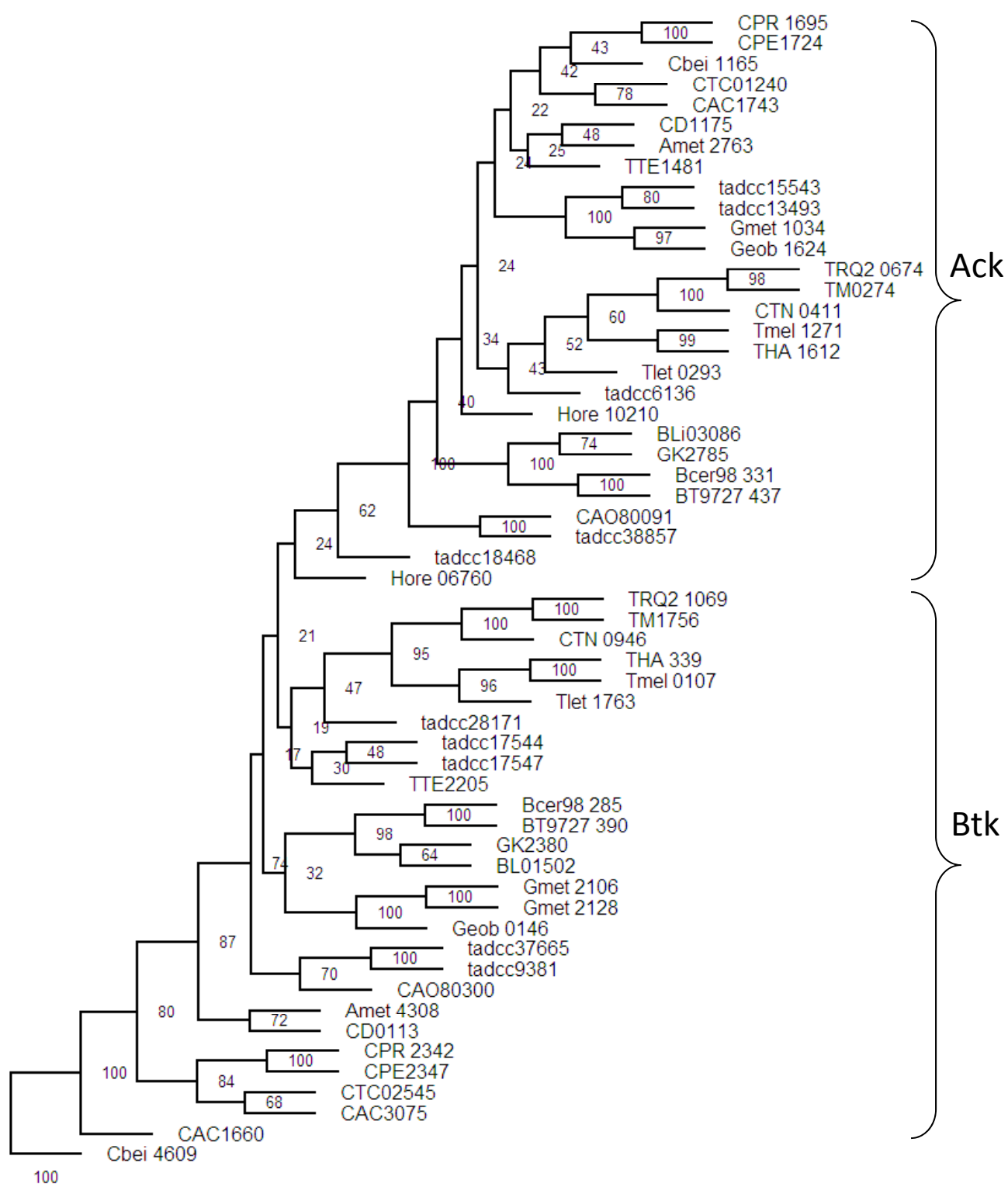
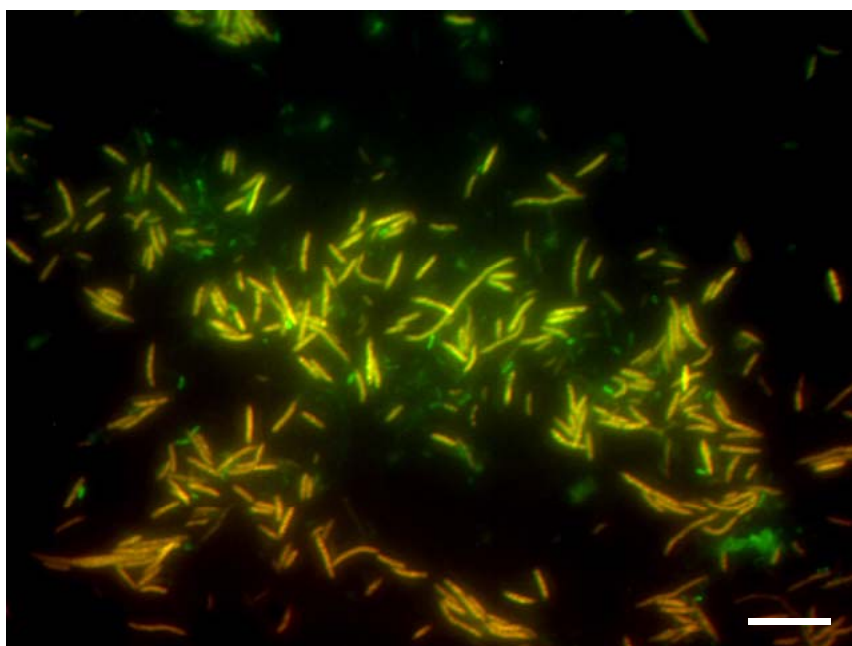
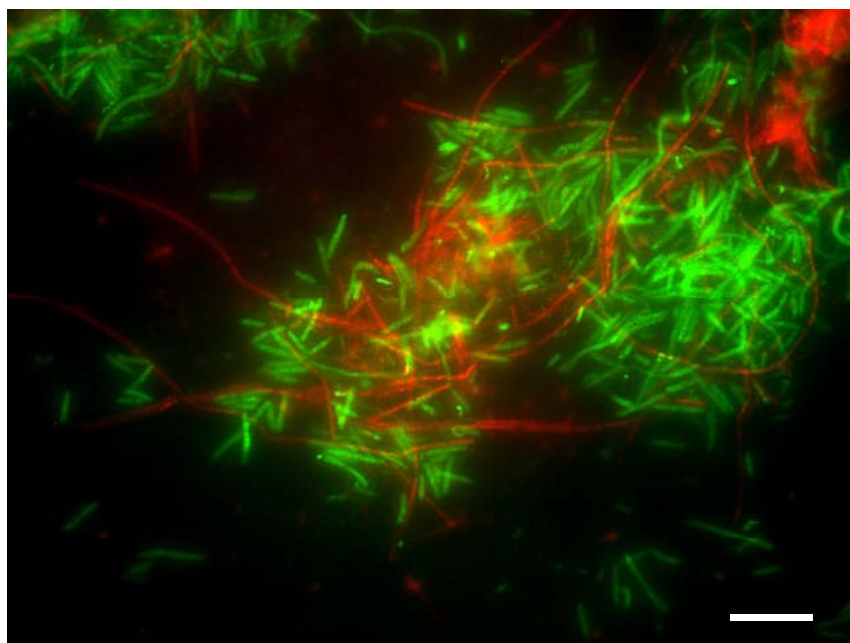


Fig. S9

(A) Biofilms (Day 430)



(B) Biofilms (Day 430)



Supplementary Table 1. Genes involved in methanogenesis pathways.

		<i>Methanolinea</i>	<i>Methanosaeta</i>
formylmethanofuran dehydrogenase	subunit A	tadcc3594, tadcc39608	tadcc27005, tadcc35500, tadcc16765
	subunit B	tadcc3593, tadcc39607	tadcc27002, tadcc25501
	subunit C	tadcc3595, tadcc39609	tadcc27004, tadcc35499
	subunit D	tadcc3592, tadcc39606	tadcc27003, tadcc35502
	subunit E	tadcc2822	tadcc27006, tadcc8453
	subunit F	tadcc3587	tadcc16469
	subunit G	tadcc3586	
	subunit H		
formylmethanofuran-tetrahydromethanopterin formyltransferase		tadcc3585, tadcc35387	tadcc6376, tadcc33681
methenyltetrahydromethanopterin cyclohydrolase		tadcc3557, tadcc37277	tadcc4083, tadcc2370
methylenetetrahydromethanopterin dehydrogenase		tadcc3651	tadcc14525, tadcc2531
methylenetetrahydromethanopterin reductase		tadcc2844, tadcc3653	tadcc29239, tadcc4464
tetrahydromethanopterin S-methyltransferase	subunit A	tadcc3607	tadcc28098
	subunit B	tadcc3606	tadcc28097
	subunit C	tadcc3605	tadcc28096
	subunit D	tadcc3604	tadcc14510
	subunit E	tadcc3603	tadcc14509, tadcc12676
	subunit F	tadcc3608	tadcc28099
	subunit G		tadcc28100
	subunit H		tadcc28101
methyl-coenzyme M reductase	α subunit	tadcc3600	tadcc5364, tadcc6053
	β subunit	tadcc3596	tadcc5367, tadcc6056
	γ subunit	tadcc3599	tadcc5365, tadcc6054
	δ subunit	tadcc3597	tadcc5366, tadcc6055
acetyl-CoA decarbonylase/synthase			

	α subunit	tadcc8401, tadcc17916	
	β subunit	tadcc8403, tadcc17919	
	γ subunit	tadcc6386, tadcc12273, tadcc26855	
	δ subunit	tadcc35692	
	ε subunit	tadcc8402, tadcc17918	
ech hydrogenase			
	subunit A	tadcc3040	
	subunit B	tadcc3041	
	subunit C	tadcc3042	
	subunit D	tadcc3043	
	subunit E	tadcc3044	
	subunit F	tadcc3045	
coenzyme F420-reducing hydrogenase			
	α subunit	tadcc3698	
	β subunit	tadcc3701	
	γ subunit	tadcc3700	
	δ subunit	tadcc3699	
Formate dehydrogenase			
	α subunit	tadcc20799, tadcc3416	tadcc34985, tadcc814
	β subunit	tadcc20800, tadcc3417	tadcc813
CoB--CoM heterodisulfide reductase			
	subunit A	tadcc3590	tadcc16468
	subunit B	tadcc3589	
	subunit C	tadcc3588	
CoB-CoM heterodisulfide reductase HdrDE			
	subunit D		tadcc23065
	subunit E		tadcc23066
Membrane bound hydrogenase			
	subunit mbhA	tadcc17854	
	subunit mbhB	tadcc17855	

subunit	tadcc17856
mbhC	
subunit	tadcc17857
mbhD	
subunit	tadcc17858
mbhE	
subunit	tadcc17859
mbhF	
subunit	tadcc17860
mbhG	
subunit	tadcc17861
mbhH	
subunit mbhI	tadcc17862
subunit mbhJ	tadcc17863
subunit	tadcc17864
mbhK	
subunit	tadcc17865
mbhL	

Supplementary Table 2. Minimum Information about a Genome Sequence

MIGS ID	Metadata Information Type	Metadata Value
MIGS 2	Investigation type	Metagenome
MIGS 3	Project Name	Wastewater Terephthalate-degrading communities from Bioreactor
	GOLD Stamp ID	Gm00012, http://genomesonline.org/GOLD_CARDS/Gm00012.html
MIGS 1.2	Trace Archive	-
	Habitat Category	Synthetic-Bioreactor
	Number of samples	4
	Project Relevance	Biotechnological, Plastic production, Wastewater treatment
MIGS 32	Relevant SOP	-
MIGS 33	Database	IMG/M, http://img.jgi.doe.gov/m
	Contact Name	Wen-Tso Liu
	Contact Email	wtliu@ad.uiuc.edu
MIGS 29	Sequencing Method	Sanger
MIGS 30	Assembly Method	PGA
MIGS 28.2	Number of Reads	-
	Gene Calling Method	Genemark
MIGS 4	Geographic Location	National University of Singapore
MIGS 4.1	Latitude	1.29973
MIGS 4.2	Longitude	103.771791
MIGS 5	Isolation Country	Singapore
MIGS 5	Collection Date	?

Supplementary text

Reactor operation

In order to enrich the anaerobic microbial consortium that degrades terephthalate, 1-liter laboratory-scale hybrid bioreactor was filled with approximately 78 packing materials (sera siporax, Sera Germany) in the upper part of the reactor and seeded with sludge obtained from mesophilic upflow anaerobic sludge bed reactors treating dimethylterephthalate (Fig. 1a). The reactor temperature was controlled under 46-50°C from Day 1 by recirculating heated water through a double-jacket column. Terephthalate (TA) was used as the sole carbon and energy source in the synthetic wastewater (Angelidaki et al., 1990; Chen et al., 2004). The overall TA loading per day was gradually increased from 0.7 to 3.6 (g TA l⁻¹ • day⁻¹) by increasing the TA concentration in the influent or decreasing the hydraulic retention time (HRT). During the reactor operation, reactor performance was constantly monitored based on the TA removal efficiency. Terephthalate was measured by a high-performance liquid chromatography (model FCV-10AL, Shimadzu, Japan) equipped with an Eclipse XDB-C18 column (Agilent, USA) and an SPD-M10A UV-detector. In addition, the TA concentration was also measured using spectrophotometer under a UV wavelength of 239 nm. Biomass was collected only from the packing materials on Days 221 and 280, and from both the packing materials and sludge bed on Days 346, and 430 for further microbial analyses. During each sampling point, 10 filters with mature biofilms were retrieved from the reactor and replaced with 10 new filters. This ensured that freshly grown biofilms during a period of 60 to 80 days could be recovered from the last three sampling points.

DNA extraction and 16S rRNA clone library

Genomic DNA from those samples taken at different time points was extracted using a protocol described previously (Liu et al., 1997). 16S rRNA gene libraries were generated for each sample taken based on a protocol described previously (Chen et al., 2004). The following primer sets, 27F (5'-AGAGTTTGATCCTGGCTCAG) and 1391R (1391R primer (5'-GACGGGCRGTGWGTRCA)) for bacterial 16S rRNA and 4aF (5'-TCCGGTTGATCCTGCCRG) and 1391R for archaeal 16S rRNA gene amplification (Hugenholtz and Goebel, 2001), were used. All libraries were sequenced from both ends and the data were analyzed using ARB software (Ludwig et al., 2004).

Rarefaction curve

16S rRNA gene sequences were aligned against the Greengenes database using the NAST alignment tool (DeSantis et al., 2006). The aligned sequences were imported into ARB software. A distance matrix was constructed and this served as the input to DOTUR (Schloss and Handelsman, 2005) for the clustering analysis of sequences into OTUs at defined sequence identity. Based on the OTU analysis, the rarefaction curves were generated.

Fluorescence in-situ hybridization (FISH)

FISH were performed on paraformaldehyde-fixed samples (Amann et al., 1995) according to the procedures described previously (Chen et al., 2004). The oligonucleotide probes used included EUBmix (i.e., EUB338, EUB338-II, EUB338-III) that targets most of the *Bacteria* (Amann et al., 1995; Daims et al., 1999), ARCH915 that targets most of *Archaea* (Amann et al., 1995), and specific probes that target different phylogenetic groups, for example, the *Desulfotomaculum* group (Loy et al., 2002; Imachi et al., 2006).

Metagenome sequencing

DNA samples taken from the surface of the filters at Days 221, 280, and 430, as well as the sludge bed sample at Day 430, were used. Three whole genome shotgun libraries, containing inserts of ~3, 8 and 40kb, were created for each of the four DNA samples (http://www.jgi.doe.gov/sequencing/protocols/protos_production.html). Initially 10 Mb of sequence from a 3 kb library was generated for each time point. For the Day 430 biofilm sample, an additional 68 Mb were sequenced from the short-insert library in addition to a small amount from 8 kb and 40 kb (fosmid) libraries (5 Mb and 3 Mb, respectively). As the microbial community composition among biofilms samples taken at Day 221, 280 and 430 are similar (Fig. 1a), the sequence data were pooled together with that obtained from the sludge bed sample at Day 430, and assembled using the PGA assembler.

Metagenome analysis

The identification of COG families was based on the IMG/M database, using a cut-off of 20% identity and e-value 0.01. Phylogenetic marker COGs were generated manually based on the occurrence of each COG family in finished isolate genomes. Phylogenetic marker COGs constitute a set of 101 COGs that are found once or twice in at least 90% of the complete isolate genomes. We used this COG set to estimate the size of the OP5 genome since there is no any closely related isolate genomes.

For the remaining populations we estimated genome size based on the Phylogenetic Distribution of Genes tool in IMG/M (Markowitz et al., 2008). This tool allows the assessment of the composition of a metagenome based on the distribution of the best BLAST hits on isolate genomes. For example, there are 1735 genes in *Pelotomaculum thermopropionicum* that are best-BLAST hits to genes from the metagenome dataset. Given that *P. thermopropionicum* contains 2920 protein coding genes we estimate that we have covered $(1735/2920) \times 100 = 59.4\%$ of the

genome. This was a conservative estimate given the expected variation in gene content among members of a genus. However, there was no other better way.

For sequence-composition based binning, a sequence-composition based taxonomic classifier for the phylogenetic binning of the sequence sample was created from sample-specific sequence data and available isolate genome sequences as described before (McHardy et al., 2007). Sample-specific training data for the sample populations were identified based on phylogenetic marker genes, comprising data for an uncultured *Methanomicrobiales* species (2 contigs, 171,430 bp), a *Methanosaeta* species (8 contigs, 73,335 bp) and a species of the candidate phylum OP5 (7 contigs, 48,419 bp). At the ranks of species, genus and order, models were trained with sample-specific sequences and sequenced genomes and combined with higher level models for clades at the ranks of class, phylum and domain, created from available isolate genome sequences. At the species level, the model contains classes for the three sample-specific populations trained with sample-specific data, as well as classes for *Pelotomaculum thermoproprium*, “*Syntrophus aciditrophicus*”, and *Candidatus Cloacamonas acidaminovorans*, trained with sequence data from one genome each. At the genus level, the model includes additional classes for *Methanosaeta* and *Geobacter*, trained with data from sequenced genomes and sample-specific data for the uncultured *Methanosaeta* population. At the order level, the model contains classes for the *Methanomicrobiales* and *Methanosarcinales*, trained with data from sequenced genomes and the sample-specific data for the respective populations. Thermotogae was not included as a clade in the model. We had no sample-specific training data for the populations from WWE1 and thus could not model these directly, nor WWE1 directly (which requires data from 2 or more different species, so e.g. one sequenced genome and sample-specific data). We mainly checked for chimeras in the sequences of the

genes discussed in the Results section. We used the SNP BLAST tool of IMG/m that aligns reads to assembled nucleotide sequences to check for misassembled contigs.

The generation of McrA and Ack amino acid sequence alignments was performed using Clustalw (Thomson et al., 1994). The phylogenetic tree of McrA was constructed using Clustalw and the Ack phylogenetic tree was constructed using the Phylip package (<http://evolution.genetics.washington.edu/phylip.html>).

The present work complies with the minimum information about a genome sequence (MIGS) (Table S2) (Field et al., 2008).

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