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Microscale sulfur cycling in the phototrophic pink berry consortia of the Sippewissett Salt Marsh

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Summary

Microbial metabolism is the engine that drives global biogeochemical cycles, yet many key transformations are carried out by microbial consortia over short spatiotemporal scales that elude detection by traditional analytical approaches. We investigate syntrophic sulfur cycling in the ‘pink berry’ consortia of the Sippewissett Salt Marsh through an integrative study at the microbial scale. The pink berries are macroscopic, photosynthetic microbial aggregates composed primarily of two closely associated species: sulfide-oxidizing purple sulfur bacteria (PB-PSB1) and sulfate-reducing bacteria (PB-SRB1). Using metagenomic sequencing and 34S-enriched sulfate stable isotope probing coupled with nanoSIMS, we demonstrate interspecies transfer of reduced sulfur metabolites from PB-SRB1 to PB-PSB1. The pink berries catalyse net sulfide oxidation and maintain internal sulfide concentrations of 0–500 μM. Sulfide within the berries, captured on silver wires and analysed using secondary ion mass spectrometer, increased in abundance towards the berry interior, while δ34S-sulfide decreased from 6‰ to −31‰ from the exterior to interior of the berry. These values correspond to sulfate–sulfide isotopic fractionations (15–53‰) consistent with either sulfate reduction or a mixture of reductive and oxidative metabolisms. Together this combined metagenomic and high-resolution isotopic analysis demonstrates active sulfur cycling at the microscale within well-structured macroscopic consortia consisting of sulfide-oxidizing anoxygenic phototrophs and sulfate-reducing bacteria.

Introduction

Microbial redox metabolism drives biogeochemical cycles and exerts a profound influence over the flux of energy throughout global ecosystems (Schlesinger, 1997; Falkowski et al., 2008). Recent work in diverse environments, from the deep sea to the human gut, has demonstrated that many of these essential ecosystem processes are mediated not by a single species but by the metabolic interactions of syntrophic microbial consortia (Boetius et al., 2000; Orphan et al., 2002; Overmann and Schubert, 2002; Schink, 2002; Hansen et al., 2011). Syntrophy, a mutualistic interaction based on the exchange of metabolites, allows microbes to exploit metabolic niches that are otherwise inaccessible to a single species (Overmann and van Gemerden, 2000; Schink, 2002; Orphan, 2009).

In closely associated microbial consortia, electron donors and acceptors are transferred over minute distances from cell to cell and drive micrometer-scale biogeochemical cycling. This tightly coupled metabolic
activity occurs on spatiotemporal scales that often elude detection by traditional analytical approaches. However, these ‘cryptic’ transformations have major implications for the dynamics of biogeochemical cycling in the macroscale ecosystem (Canfield et al., 2010; Holmkvist et al., 2011; Stewart et al., 2012). Understanding the structure and function of this intricate microbial metabolic network is essential for accurate modelling of biogeochemical cycles (Treseder et al., 2011), prediction of the ecosystem dynamics following perturbations (Allison and Martiny, 2008), and interpretation of net contribution of microbial interactions to bulk measurements of the geochemical environment (Brüchert, 2004; Fike et al., 2009).

Photosynthetic microbial mats and aggregates provide an excellent system to investigate the influence of microbial metabolic interactions over biogeochemical processes at the micrometer scale (Canfield and Des Marais, 1993; Decker et al., 2005; Baumgartner et al., 2006; 2009; Fike and Grotzinger, 2008; Fike et al., 2008; Petroff et al., 2011). The ‘pink berries’ (Fig. 1) are visually striking photosynthetic aggregates of uncultured microbes found in the Little and Great Sippewissett salt marshes (Falmouth, MA). Reaching up to a centimetre in diameter, these aggregates are found at the sediment–water interface of intertidal pools surrounded by tall-form smooth cordgrass (*Spartina alterniflora*). The berries have been studied for over three decades as a part of the Microbial Diversity summer course at the Marine Biological Laboratory in Woods Hole, MA (Gibson et al., 1984). Initial characterizations revealed that the primary biomass of the aggregates is composed of anoxygenic phototrophs, purple sulfur bacteria of the family *Chromatiaceae* (Seitz et al., 1993). Respiratory activity and the dense exopolymer matrix create anoxic conditions immediately

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**Fig. 1.** A. Intertidal pools in Little Sippewissett Salt Marsh form dense stands of pink berry aggregates at the sediment–water interface. B. Large aggregates can reach nearly a centimeter in size. C. Pink berries in sediment (0–5 cm) collected from an intertidal pool in Little Sippewissett. D. Berries can be easily washed free of marsh sediment and manipulated in the lab. E. Cross-section of a berry reveals pink tubules encased in a clear exopolymer matrix, scale bar is 0.5 mm. F. Higher magnification view of pink berry tubules, scale bar is 200 μm.
below the aggregate surface, though net sulfide production had not been detected (Seitz et al., 1993).

We show that the pink berries are formed by a consortium of purple sulfur bacteria (PSB) and sulfate-reducing bacteria (SRB) that form a specific interspecies association involving direct transfer of sulfur species. The present study of the pink berries utilizes a holistic approach to track sulfur metabolic interactions at the microbial scale, from draft genomes to ecophysiology. Investigation of community diversity and metabolic function using 16S rRNA gene surveys, microscopy and shotgun metagenomics generated hypotheses about the cycling of sulfur and exchange of nutrients within the aggregates. A suite of geomicrobiological tools from microvoltammetry to radio- and stable isotope approaches were employed to interrogate these predictions, illustrating the microbial dynamics and geochemical signatures of this cryptic microscale sulfur cycle.

**Results**

**Phylogenetic diversity in the pink berry consortium: 16S rRNA gene surveys**

Analysis of 16S rRNA genes found in pink berry aggregates demonstrate a consistent, simple community where two phylotypes (defined at 97% sequence identity clustering) account for more than 65% of the sequenced clones (total of 273 sequences from three samples, Fig. 2A).

![Fig. 2. A. 16S rRNA gene sequences isolated from pink berries which were collected from Penzance Point marsh in 2011 (89 clones), and Little Sippewissett marsh in 2010 (94 clones) and 2007 (90 clones). Two operational taxonomic units (OTUs), a purple sulfur bacteria (PB-PSB1) and sulfate-reducing bacteria (PB-SRB1), account for more than 60% of the sequences observed.](image-url)

**Fig. 2.** A. 16S rRNA gene sequences isolated from pink berries which were collected from Penzance Point marsh in 2011 (89 clones), and Little Sippewissett marsh in 2010 (94 clones) and 2007 (90 clones). Two operational taxonomic units (OTUs), a purple sulfur bacteria (PB-PSB1) and sulfate-reducing bacteria (PB-SRB1), account for more than 60% of the sequences observed. B. Maximum-likelihood phylogeny of the full-length PB-SRB1 OTU and related Desulfobulbaceae. Environmental sequences from uncultured organisms are shown in gray. Bootstrap support (500 replicates) greater than 50% are displayed at the nodes. Branch lengths (and scale bar) correspond to the mean number of nucleotide substitutions per site on the respective branch.

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PB-PSB1, the most abundant phylotype (35–53% of sequences), is an uncultured species of purple sulfur bacteria (PSB) belonging to the Halochromatium–Thiohalocapsa lineage of the Chromatiaceae (Supporting Information, Fig. S1).

The second most abundant phylotype, PB-SRB1 (15–35% of sequences), is most closely related to Desulfofustis glycolicus, a glycolate-oxidizing sulfate-reducer in the family Desulfobulbaceae (Fig. 2B). Uncultured organisms closely related to PB-SRB1 were often found in association with organisms that participate in sulfide-oxidizing symbioses or in environments dominated by sulfide oxidation (either chemotrophic or phototrophic, Fig. 2B). In addition to the dissimilatory reduction of sulfate, isolates from the genera Desulfofustis and Desulfocapsa have been shown to grow by the disproportionation of elemental sulfur and thiosulfate in the presence of an exogenous sulfide scavenger (Finster et al., 1998; Finster, 2008).

The remaining 16S rRNA gene sequences are predominantly chloroplasts from marine diatoms and diverse phylotypes from the phylum Bacteroidetes. Dominant phylotypes of Bacteroidetes belong largely to clades of environmental sequences from areas of known or suspected active sulfur cycling, with few cultured representatives (Supporting Information, Fig. S2). Analysis of 18S rRNA gene sequences amplified from pink berries revealed several different phylotypes related to pennate diatoms and dinoflagellates (Supporting Information, Fig. S3). For the purposes of this work, we have focused further analysis on the dominant berry phylotypes, PB-PSB1 and PB-SRB1.

**In-situ identification and spatial arrangement**

Pink berries are composed of irregularly shaped pink tubules in a transparent exopolymer matrix (Fig. 1F). Confocal microscopy of pink berry thin sections revealed that these tubules are dominated by purple sulfur bacteria, identified as autofluorescent cocci (2–4 μm in diameter) containing refractile elemental sulfur inclusions (Fig. 3). These refractile inclusions were labile in solvents (methanol, ethanol) and detergents (SDS, Triton X100), corroborating their identification as intracellular elemental sulfur globules. These cells were also fluorescently labelled by catalysed reporter deposition–fluorescence in situ hybridization (CARD-FISH) using the GAM42a group-specific probe which hybridizes to 16S rRNA from Gammaproteobacteria (Manz et al., 1992; Supporting Information, Fig. S4).

PB-SRB1 species was localized via CARD-FISH with a phylotype-specific probe (SRB-PiBe213; this study) designed from the 16S rRNA gene libraries. The SRB-PiBe213 probe hybridized to 3-μm-long rods that were abundant and interspersed throughout the

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**Fig. 3.** Epireflective confocal microscopy of sectioned pink berry tissue. Autofluorescence (excitation 543 nm, emission 550–570 nm) of the purple sulfur bacteria is shown in pink, and reflective signal from the refractile elemental sulfur inclusions is shown in white.

**Fig. 4.** Identification of the berry-associated PB-SRB1 species by catalysed reporter deposition–fluorescence in situ hybridization (CARD-FISH) using a phylotype-specific probe. Scanning confocal micrograph shows a cross section of pink berry biomass from near the periphery of the aggregate. This image is an overlay of three fluorescent signals: autofluorescent purple sulfur bacteria (shown in pink, excitation 543 nm, emission 550–570 nm), CARD-FISH signal from the SRB-PiBe213 probe (shown in green, Alexa 488 tyramide) and DAPI nucleic acid stain (shown in blue).
genomic data were assessed using both ribosomal RNA abundance and diversity of different taxa in the metagenomic read sets. The metagenomic data, which avoids the bias inherent in assembling the reads, was also investigated using unassembled Illumina shotgun metagenomics. The diversity of the microbes in the pink berries was shown to contain microscopic aggregates of coccolid PSB cells in association with rod-shaped cells hybridizing to the SRB-PiBe213 probe. The smallest aggregations contained only 5–6 total cells, while larger microaggregates were 20–50 μm in diameter (data not shown).

**Metagenomic analysis of phylogenetic diversity**

The diversity of the microbes in the pink berries was also investigated using unassembled Illumina shotgun metagenomic reads. The abundance and diversity of different taxa in the metagenomic data were assessed using both ribosomal RNA gene sequences (Meyer et al., 2008) and conserved phylogenetic marker genes (Darling et al., 2014). The diversity observed in the shotgun metagenomic sequences recapitulated that of the PCR-based surveys (Fig. 5). A notable exception was the presence of significant numbers of Alphaproteobacteria (Oceaciola and Oceanicaulis species) and the Rhodospirillales. This discrepancy is likely due to bias introduced by the ‘universal’ 8F bacterial primer which poorly covers the organisms from these orders, according to in-silico specificity searches against the SILVA and Ribosomal Database Project (RDP) databases (data not shown).

Further metagenomic analysis of microbial diversity was conducted with co-assembled Roche 454 Titanium and Illumina HiSeq sequence data. Strategies optimized for community genomics (Peng et al., 2012) were used to assemble 7400 scaffolds greater than 1 kilobase (kb): N50 1.6 kb, max contig 64 kb. Clustering of metagenomic scaffolds (see Experimental procedures) revealed two well-defined bins belonging to PB-PSB1 (20-25x coverage) and PB-SRB1 (15-20x coverage). The depth of coverage from these genomic bins corresponded to the abundance of PB-SRB1 to PB-PSB1 observed in the 16S rRNA gene PCR data (1 PB-SRB1 RB per 1.1–1.7 PB-PSB1 cells). These genomic bins represent near-complete genomes for both PB-SRB1 and PB-PSB1, as assessed by assembled sequence length, number of coding features and an analysis of 45 single copy phylogenetic marker genes (see Supporting Information, Table S1). In the present study, we have focused further analysis of these genomes on the pathways related to sulfur-based metabolism of these organisms.

**Metagenomic evidence for sulfur cycling**

To assess the diversity of sulfur-cycling organisms in the berries, we mapped unassembled metagenomic sequence reads to the phylogeny of dissimilatory sulfite reductase genes (dsrAB, see Experimental procedures), which are widely used phylogenetic markers for both oxidative and reductive dissimilatory sulfur metabolisms (Loy et al., 2008). Approximately 33% of reads aligning to the dsrAB sequence could not be taxonomically classified by this approach, likely because they originated from phylogenetically uninformative regions of the dsrAB genes. Most classified reads were placed in either the Chromatiaceae (44%) or Desulfobulbaceae (13%, Supporting Information, Fig. S5). Within these families, the bulk of the reads were assigned to Halochromatium salexigens (Chromatiaceae) and Desulfobulbus glacieus (Desulfobulbaceae), in congruence with the phylogenetic affiliation of the dominant 16S rRNA gene sequences. The
remaining classified reads (10% of total aligned reads) were distributed amongst Desulfobacteraceae and Desulfotomaculum.

To further characterize the potential for sulfur redox cycling with the pink berries, we identified pathways for both sulfate reduction and sulfide oxidation from the complete assembled metagenomic dataset. While many of the same genes are used in both reductive and oxidative pathways, the homologues can be clearly distinguished both by divergent sequence and genomic context. All identified sulfur oxidative genes were found on scaffolds binned to PB-PSB1 by the independent sequence composition-based analysis, while sulfur reductive genes were located on scaffolds in the PB-SRB1 bin. Detailed discussion of the oxidative and reductive metabolic pathways in the PB-PSB1 and PB-SRB1 genomes is presented in the Supporting Information S1, Supporting Information S2, Table S2 and Figs S7–12.

Illuminated microcosms of berries in anoxic filter-sterilized marsh water did not produce sulfide detectable by the Cline assay (Cline, 1969), but instead rapidly consumed 1 mM of added sulfide over the course of two days (Fig. 6A). To investigate the sulfur speciation and redox environment within the aggregates, we conducted cyclic voltammetry using a gold amalgam microelectrode inserted into a large berry (~0.5 cm diameter). Voltammograms measured from the aggregate interior revealed a peak at a potential of 0.85 V (vs. Ag/AgCl), which changed as the electrode penetrated into and back out of the berry. This measurement corresponds to concentrations of sulfide between 13 and 41 μM at different points inside the berry (Fig. 6B; see also Supporting Information, Fig. S6). Independent analyses inside other large berries using a Clark-type sulfide microelectrode (Unisense, Aarhus, Denmark) indicated the presence of 5–20 μM H₂S (135–540 μM of total sulfide). No other electroactive species detectable by cyclic voltammetry (e.g. O₂, Fe³⁺, Fe²⁺, Mn²⁺ and As³⁺, tetrathionate, dissolved/nanoparticulate elemental sulfur) were observed within the berries.

To investigate the isotopic composition of sulfide evolved within the berries, large aggregates (~0.5 cm diameter) were threaded onto 24 gauge silver wires and incubated overnight in situ (Fig. 7A). Soluble sulfide was precipitated onto the wire as silver sulfide, leaving a dark tarnish with metallic sheen underneath each aggregate (Fig. 7B). Visible sulfide accumulation began just beneath the surface of the aggregate, with the darkest sulfide deposition towards the centre of the aggregate, confirming reports of sulfide from both microvoltammetry and sulfide microsensors. The abundance and isotopic composition of this precipitated silver sulfide was subsequently analysed using an IMS 7f-GEO magnetic sector secondary ion mass spectrometer (SIMS; CAMECA, Gennevilliers, France), following methods described by Fike and colleagues (2009). A transect along the wire that passed through two berries showed increasing ³²S counts...
The $\delta^{34}$S of deposited sulfide ranged from $\sim 6\%$ at the edge of the aggregates to $\sim 31\%$ in the centre of one of the aggregates. Sulfide deposited at the centre of the second berry in the transect showed lower $^{32}$S counts and less isotopic depletion ($\delta^{34}$S of $-20\%$) relative to the first berry (Fig. 7C). The water in the intertidal pond had a sulfate $\delta^{34}$S of $+22\%$; hence, these 'intra-berry' isotopic values indicate isotopic fractionations from $\sim 15\%$ to $53\%$. In contrast, silver wires that were incubated at the sediment surface nearby but not penetrating the berries (e.g. the loop at far left in Fig. 7A) had $\delta^{34}$S of $-16 \pm 2\%$ (average $\pm$ SD, $n=15$) uniformly distributed along the wire.

**Investigating sulfur cycling with stable isotope probing using $^{34}$SO$_4$ and nanoSIMS**

To track the activity of the sulfur metabolism and cycling between members of the consortia, freshly collected pink berries were incubated anaerobically with $^{34}$S-enriched sulfate and $^{13}$C-enriched bicarbonate under both light and dark conditions. Enrichment of $^{34}$S in the morphologically distinctive PB-PSB1 cells was evident after 4 days of incubation (Fig. 8A and B). The $^{34}$S/$^{32}$S ratio in these cells was approximately twice that observed in unlabelled control conditions. This signal was found to be labile in methanol (Fig. 8C), a solvent used for the quantitative extraction of elemental sulfur (Ferdelman et al., 1997). Enrichment in $^{34}$S was documented in both light and dark incubations (Fig. 8C).

Accumulation of the $^{34}$S isotope label appears to be dependent upon the activity of the sulfate-reducing organisms in the aggregate; addition of sodium molybdate (NaMoO$_4$), an inhibitor of sulfate reduction (Oremland and Capone, 1988), blocked the incorporation of the $^{34}$S-enriched label (Fig. 8C). Pronounced $^{34}$S-enrichment ($1100 \pm 200\%$ for three replicate incubations) was observed in bulk berry biomass from incubations with $^{34}$S-enriched sulfate, as determined by elemental analyser–isotope ratio mass spectrometry (Supporting Information, Fig. S13). Unlabelled controls and molybdate-treated bulk biomass had isotopic composition comparable with that of native berries sampled directly from the marsh ($\delta^{34}$S values ranging from $-15\%$ to $-24\%$).

Carbon fixation was light-dependent, as assessed by both nanoSIMS measurements of $^{13}$C-incorporation (Fig. 8C) and radiolabelled ($^{14}$C) bicarbonate incubation assays (Fig. 8D), indicating that PB-PSB1 acts as the primary producer in the aggregates. Molybdate incubations did not affect the light-dependent fixation of carbon in short-term incubations (1–4 h), indicating that PB-PSB1 is not directly inhibited by molybdate (Fig. 8D). In the 4-day incubations, molybdate was found to decrease the...
aggregates’ carbon fixation in the light, suggesting that longer-duration molybdate treatment imposes sulfide limitation, thereby decreasing the primary productivity of PB-PSB1 (Fig. 8C).

Discussion

Tightly coupled microbial consortia modulate biogeochemical cycles over spatiotemporal scales that often
sulfur cycling at the microscale. Based on the combination of phylogenetic information (i.e. the physiology of these species’ cultured relatives) and the conserved spatial structure of the pink berries, we hypothesized that intraberry sulfate reduction by PB-SRB1 provides a local source of sulfide for PB-PSB1 (Fig. 9). Such an association would allow PB-PSB1 to maintain photosynthetic activity even when exogenous sulfide is low or absent, such as during peak light conditions when the chemocline shifts down in the sediment by several centimetres relative to its nighttime levels (Revsebech et al., 1983; Dillon et al., 2009).

Electron donors driving sulfate reduction could either be locally supplied from photosynthate or exogenously from the sediment (Fig. 9). Metagenomic sequencing confirmed the genetic potential for this intraberry sulfur cycle; the complete metabolic pathways for sulfate reduction and sulfide oxidation were present in the genomes of PB-SRB1 and PB-PSB1, respectively.

To test this metabolic model, high-resolution geochemical methods (SIMS, nanoSIMS, microvoltammetry) were used to track the cryptic sulfur cycle from sulfur metabolite pools to cell-specific sulfur assimilation and biomolecules. Sulfur-34 stable isotope labelling allowed us to follow the flow of sulfur within the aggregate, from the reduction of sulfate by PB-SRB1, to interspecies transfer and incorporation into PB-PSB1 cells. After incubation with 34S-enriched sulfate, we observed punctate, solvent-labile sulfur-34 enrichment in PB-PSB1 cells (Fig. 8) that is consistent with accumulation of labelled sulfur in intracellular sulfur globules (Fig. 3).

This sulfur-34 enrichment of PB-PSB1 is unlikely to occur via direct incorporation of the isotopically labelled sulfate. The cellular sulfur of Chromatiaceae species is dominated by periplasmic stores of elemental sulfur (34% of total cell weight), which is exclusively derived from the reduced sulfur pool (Dahl and Prange, 2006). Furthermore, many Chromatiaceae, including the closest cultured relatives to PB-PSB1, are unable to assimilate sulfate (Dahl, 2008; Kumar et al., 2009). Even in those species that can assimilate sulfate, this process is thought to be repressed during anoxic photolithotrophic growth (Neumann et al., 2000; Sander and Dahl, 2008). During photo-organotrophic growth, the model Chromatiaceae species Allochromatium vinosum assimilates sulfate via the cystTWA sulfate ABC transporter and the cysDN assimilatory ATP-sulfurylase. Homologues of these genes were not found in the PB-PSB1 genome, and searches against the complete assembled metagenomic data recovered only distant sequence matches from genes more closely related to those from organisms in the Bacteroidetes, Alphaproteobacteria or Desulfovibacterae.

As direct 34S-sulfate incorporation by PB-PSB1 cells is unlikely, we propose that PB-SRB1 reduced the 34S-sulfate label to sulfide, which was then taken up and
re-oxidized to elemental sulfur by PB-PSB1 (Fig. 9). Consistent with this interpretation, we found that pink berries rapidly oxidized sulfide (Fig. 6A) and that accumulation of the $^{33}$S-label in PB-PSB1 was dependent upon the activity of the sulfate-reducing bacteria (Fig. 8C). Sulfur-34 enrichment was not observed when sulfate reduction was inhibited by sodium molybdate. While the application of ‘specific’ inhibitors (such as molybdate) to mixed microbial populations can have unintended consequences on non-target organisms (Oremland and Capone, 1988), we have verified that PB-PSB1 were not directly inhibited by molybdate by demonstrating infrared light-dependent carbon fixation during short (1–4 h) incubations in the presence of exogenous sulfide (Fig. 8D). In longer incubations where exogenous sulfide became limiting (4 days), molybdate treatment diminished the light-batteries where exogenous sulfide became limiting (4 days), molybdate treatment diminished the light-dependent fixation of carbon (Fig. 8C). This decrease in primary productivity with SRB inhibition supports the hypothesis that syntrophically supplied sulfide buffers PB-PSB1 from episodic sulfide deprivation.

Having established the importance of sulfate reduction in the pink berry consortia, we sought to describe the pools of reduced sulfur within the pink berries. The close physical association of PB-SRB1 and PB-PSB1 (Fig. 4) suggests that re-oxidation of reduced sulfur species occurs over very short spatiotemporal scales. Sulfide could not be detected by a previous study with Clark-type sulfide microelectrodes (Seitz et al., 1993), and we were only able to occasionally measure micromolar concentrations of sulfide inside very large aggregates using microvoltammetry and Clark-type sulfide microelectrodes (Fig. 6B). The ephemeral nature of the sulfide pool supports our predictions for rapid sulfide consumption in this closely coupled metabolic partnership. Under the conditions we describe, the pink berries were observed to be net sulfide consumers. However, this balance between consumption and production is likely influenced by many factors (e.g. intensity and duration of the photoperiod, temperature, electron donor supply), and further studies are necessary to better elucidate determinants of sulfide flux in the consortia.

The most likely source of this sulfide detected within the berries is the reduction of sulfate by PB-SRB1. However, sulfide could also be produced by several other metabolic processes (Fig. 9), including: (i) reduction of elemental sulfur by PB-SRB1, (ii) disproportionation of elemental sulfur or thiosulfate by PB-SRB1 or (iii) PB-PSB1’s dark phase respiration of stored carbohydrates and concomitant reduction of periplasmic elemental sulfur reserves, producing polyhydroxyalkanoates and sulfide (van Gemerden, 1968; Rothermich et al., 2000). To further understand the geochemistry of the pink berry sulfate cycle, we characterized both the spatial distribution and stable isotopic composition of this intraberry sulfide.

Differences in stable isotope ratios between oxidized and reduced pools of sulfur are widely used for modern and paleoecological reconstructions of the sulfur cycle (Canfield and Teske, 1996; Habicht et al., 1998; Canfield, 2001; Hurtgen et al., 2005; Fike et al., 2006; Fike and Grotzinger, 2008; Sim et al., 2011a). Sulfide oxidation mediated by anoxygenic phototrophs (e.g. PB-PSB1) is thought to have minimal impact on the fractionation of sulfur isotopes (Ivanov et al., 1977; Fry et al., 1984; 1985; Zerkle et al., 2009). However, both sulfate reduction and sulfide disproportionation can produce sulfide that is significantly depleted in heavy stable isotopes relative to the starting pool of sulfate (Canfield, 2001; Sim et al., 2011a). Though use of sulfur isotopic fractionation to make inferences about sulfur cycling is widespread, our understanding of the microbial metabolic information encoded in these measurements is based largely on pure-culture studies of single species (Kaplan and Rittenberg, 1964; Kemp and Thode, 1968; Sim et al., 2011b) or on in situ geochemical measurements where the microbial community was poorly characterized (Habicht and Canfield, 2001; Brüchert, 2004).

The millimetre-sized pink berry consortia provided a well-constrained multispecies ecosystem in which to examine micron scale spatial variation in sulfur isotopic composition ($\delta^{34}$S$_{\text{sulfide}}$). The use of sulfide capture on silver wire, a technique originally used for radiotracer $^{35}$S measurements (Cohen, 1984; Visscher et al., 2000; Dubilier et al., 2001), coupled with SIMS $\delta^{34}$S measurements, elucidated gradients of increasing sulfide concentration and isotopic depletion (lower $\delta^{34}$S values) from the periphery to the centre of large pink berries (Fig. 7). These isotopic geochemical gradients observed in the berries are similar to $\delta^{34}$S$_{\text{sulfide}}$ trends observed from SIMS transects on silver discs through the oxycline of the Guerrero Negro photosynthetic mats (Fike and Grotzinger, 2008; Fike et al., 2008; 2009).

The range of sulfide–sulfate fractionations observed in the berries (15‰ at the periphery to 53‰ at the aggregate centre) is consistent with values reported from pure cultures of sulfate-reducing bacteria which can range from $\sim 0$‰ to 66‰ (Sim et al., 2011a). Large isotopic fractionations, such as those observed in the centre of the berries, can be produced by either (i) slow-growing sulfate-reducing bacteria cultured with refractory or growth-limiting concentrations of electron donors (Sim et al., 2011a,b; Leavitt et al., 2013), or (ii) step-wise fashion from the coupled metabolic activities of reductive and oxidative processes (e.g. phototrophic sulfide oxidation by PB-PSB1 or intermediate oxidation state sulfur disproportionation by PB-SRB1; see Supporting Information S1 for more detailed discussion of mechanisms that could have produced the observed isotopic gradients).
Cultured relatives of PB-SRB1 in the genera Desulfofusit is and Desulfocapsa are capable of both sulfate reduction and the disproportionation of elemental sulfur or thiosulfate (Finster, 2008), corroborating our isotopic findings which suggest disproportionation could contribute to the pink berry sulfide pool. Both ecophysiological and genomic data strongly supports the conclusion that PB-SRB1 is capable of sulfate reduction, though genomic evidence for the disproportionation of elemental sulfur or thiosulfate by PB-SRB1 remains less clear. The exact suite of genes required for disproportionation is still unknown, despite the recent sequencing of Desulfocapsa sulfexigens, a sulfur disproportionator incapable of sulfate reduction (Finster et al., 2013). The sulfur disproportionation pathway appears to involve many of the same genes used in sulfate reduction, in addition to a sulfite-oxidoreductase enzyme (Frederiksen and Finster, 2003) for which there are several candidates in genomes of PB-SRB1 and D. sulfexigens (Finster et al., 2013).

In pure culture, growth by elemental sulfur disproportionation has been described only in the presence of a sulfide sink that keeps the exogenous sulfide concentration low, providing thermodynamically favourable conditions for this reaction (Canfield et al., 1998; Finster, 2008). Phototrophic consumption of sulfide by PB-PSB1 provides a biotic sulfide sink in the consortia that could create an attractive niche for elemental sulfur disproportionation, with both abundant sulfur deposits and low concentrations of sulfide. Should sulfide reach higher concentrations, disproportionation of polysulfides could become an important portion of the metabolic strategy of PB-SRB1. Recent studies of anaerobic methane-oxidizing consortia suggest that at least some sulfate-reducing consortia members can disproportionate disulfide that forms in sulfidic environments by the abiotic reaction of elemental sulfur with sulfide (Milucka et al., 2012).

**Conclusion**

Tracking the interspecies metabolic exchanges that drive microscale biogeochemical processes in natural microbial communities remains a technical challenge. For example, biogeochemical cycling in laminated photosynthetic microbial mats have been studied for decades (e.g., Canfield and Des Marais, 1993; Decker et al., 2005; Baumgartner et al., 2009; Petroff et al., 2011), yet the microbial interactions controlling substrate flux (Burow et al., 2013) and geochemical signatures (Fike and Grotzinger, 2008; Fike et al., 2008) are only just beginning to be understood. Using the pink berries, we demonstrate how an integrative microbial and microgeochemical approach can be used to decrypt the microbial metabolic partnerships that drive sulfur cycling at the microscale.

This methodology, which may ultimately be used to examine more complex ecosystems, offers direct evidence of syntropic interspecies sulfur transfer.

SIMS analysis of spatial gradients in sulfide abundance and isotopic composition provide a geochemical context for this microscale sulfur cycle. We find it notable that, even within this well-described, limited diversity system, the observed isotopic variation in sulfide can be explained by a number of different plausible scenarios from sulfate reduction alone to a series of coupled reductive and oxidative processes (see also Supporting Information S1). This ambiguity indicates that care should be taken when using such data alone for reconstructions sulfur cycling in more complex sedimentary systems, both ancient and modern. While we have demonstrated the activity of one portion of the sulfur cycle (sulfate reduction and sulfide oxidation), data from our work and other sulfur-based syntrophies (Norlund et al., 2009; Milucka et al., 2012) suggest there may also exist a network of metabolic interactions involving intermediate oxidation state sulfur species (e.g. elemental sulfur, disulfide, thiosulfate) that remain to be explored.

**Experimental procedures**

**Sampling**

Unless otherwise stated, berries were sampled in June and July of 2007, 2010 and 2011 from a single intertidal pool formed in the Little Sippewissett Salt Marsh, Falmouth, MA USA (41°34′33.01″N, 70°38′21.24″W). Large berries (~0.5–1 cm in diameter) used for the silver wire sulfide capture and cyclic microvoltammetry were sampled from a second pool in Little Sippewissett (41°34′33.52″N, 70°38′9.71″W) in September 2012. Pink berries were also sampled from Penzance Point Marsh, Woods Hole, MA, USA (41°31′29.95″N, 70°41′7.48″W) and were sampled in the summer of 2011. Berries were collected from the sediment–water interface by sieving (1 mm mesh size) and were washed three times in 0.2 μM of filter-sterilized marsh water.

**SSU rRNA clone libraries and sanger capillary sequencing**

Five to 10 small aggregates were homogenized with PCR-grade water, and DNA was extracted with the MoBio PowerSoil kit (MoBio, Carlsbad, CA, USA) with a 1 min bead-beating step employed for lysis in place of the 10 min vortexing step outlined in the manufacturer’s protocol. Bacterial 16S rRNA genes and eukaryotic 18S rRNA genes were PCR-amplified, cloned, sequenced and clustered to operational taxonomic units (OTUs) at the 97% sequence similarity threshold as described in the Supporting Information S1. GenBank accession numbers for dereplicated, chimera-checked 16S rRNA gene sequence data are KF512914–KF513148, and 18S rRNA gene sequence data are KF516997–KF517018. Phylogenetic trees were constructed either with RAxML 7.2.8 (Stamatakis, 2006) with 1000 rapid
bootstrap inferences and GTRGAMMA rate approximation, or FastTree using the approximate maximum-likelihood method (Price et al., 2010) with 1000 SH-like support, GTRCAT approximation with 20 rate categories.

Metagenomic sequencing and analysis

Metagenomic sequencing. Total extracted community DNA was sequenced by Roche GS 454 FLX+, Illumina HiSeq and Illumina MiSeq technologies as described in Supporting Information S1. All quality-filtered, unassembled sequence data is available under NCBI BioProject PRJNA214436 in the Sequence Read Archive (SRA) accessions SRX332170, SRX332174 and SRX332175. Data are also available via the MG-RAST server under MG-RAST IDs 4454153.3, 4517592.3 and 4516362.3. Overlapping Illumina MiSeq paired-end reads (250 bp) were assembled, when possible, using the MG-RAST 3.3 pipeline and classified using the M5RNA database to provide a diversity description paralleling that of the 16S rRNA gene clone libraries (Meyer et al., 2008). To assess diversity of the dsrAB sulfur cycling marker genes, a Hidden Markov Model (HMM) and full-length reference tree were built from a curated dsrAB alignment (Loy et al., 2009) using the HMMER 3.0 and FastTree (Price et al., 2010) as implemented by the Phylosift pipeline (Darling et al., 2014). Using the Phylosift pipeline, Illumina sequence reads were scanned using LAST (Kiblasa et al., 2011), aligned to the reference marker with HMMER 3.0, and placed onto the full-length dsrAB phylogenetic tree using pplacer (Matsen et al., 2010).

Metagenomic assembly, genomic binning and genome completeness. Roche 454 Titanium and interleaved paired-end Illumina HiSeq data were co-assembled using the idba_ud algorithm 1.0.9 (Peng et al., 2012). Using protein queries from Desulfo bulbus propionicus and Allochromatium vinosum TBLASTn searches identifying key sulfur-cycling functional genes were conducted on nucleotide databases of this complete, assembled metagenomic data. This dataset have been deposited as a whole genome shotgun (WGS) project at DDBJ/EMBL/GenBank under the accession AVFP00000000. The version described in this paper is version AVFP01000000. Data is also available via the MG-RAST database under MG-RAST ID 4532235.3.

Contigs larger than 1 kb were binned into genomes by tetranucleotide frequencies using emergent self-organized maps as described in Supporting Information S1 and previously (Dick et al., 2009; Wrighton et al., 2012). RAST annotations of the PB-PSB1 and PB-SRB1 genomes are available at FigShare (http://dx.doi.org/10.6084/m9.figshare.770903). This draft genome project has been deposited as a WGS project at DDBJ/EMBL/GenBank under the accessions AVFQ00000000 and AVFR00000000. The versions described in this paper are version AVFQ01000000 and AVFR01000000.

Embedding and cryosectioning for microscopy and nanoSIMS

Washed berries were rinsed in phosphate-buffered saline (PBS) for 1 min and then fixed for 1 h at room temperature (4% paraformaldehyde, 0.5% glutaraldehyde in PBS). Post-fixation, berries were washed three times with PBS and incubated for > 1 h in a cryoprotectant solution (7.5% sucrose in PBS). Berries were then transferred to O.C.T. TissueTek (Sakura, CA, USA) and allowed to infiltrate for > 2 h before being flash frozen in liquid nitrogen. Frozen tissue blocks were sectioned at 10 μm thickness at –20°C using a straight-razor cryostat. Samples for CARD-FISH hybridization and epireflective confocal microscopy were placed onto Tissue Path Superfrost Plus Gold Slides (Fisher Scientific, Waltham, MA, USA), while samples for nanoSIMS were placed onto either glass rounds or indium tin oxide (ITO)-coated glass squares (Dekas and Orphan, 2011).

CARD-FISH, imaging elemental sulfur inclusions and confocal microscopy

The probe design tool of the ARB software package (Ludwig et al., 2004) was used to create specific probes for PB-SRB1 phytype found in the 16S rRNA gene clone library data. Specificity of the probe (SRB-PiBe213) for this sequence cluster was checked against the GenBank database using BLAST, the SILVA database (release 108), the Ribosomal Database Project and NCBI database, and no hits for sequences outside of the target cluster could be detected. The SRB-PiBe213 probe (5′-tcctctgcaacacgca-3′) was ordered as conjugate from Biomers (Ulm, Germany). The general gammaproteobacterial probe GAM42a probe sequence was checked and found to target the PB-PSB1 sequences.

In addition to hybridizations with the custom SRB-PiBe213 probe, GAM42a (Manz et al., 1992) and Delta495a-c with competitors a-c (Lücker et al., 2007), the eubacterial probe EUB338I-III (Amann et al., 1990; Daims et al., 1999) was used as a positive control and a nonsense probe NON338 (Wallner et al., 1993) as a control for nonspecific binding. Hybridizations and tyramide signal amplification were performed as described previously (Ishii et al., 2004) with the modifications described in detail in the Supporting Information S1. Initial imaging was conducted using a Zeiss Axio IMAGER MZ epifluorescence microscope equipped with a color camera (AxioCam HRC, Carl Zeiss, Thornwood, NY, USA). Confocal microscopy of the SRB-PiBe213 CARD-FISH hybridization was conducted using a Leica TCS SP8X confocal microscope (Leica Microsystems, Wetzlar, Germany) with a tunable white light laser.

Elemental sulfur inclusions in the purple sulfur bacterial cells were imaged by epireflective confocal microscopy using an Olympus FV1000 LSM on tissue sections as described previously (Pasteris et al., 2001). Briefly, the 488 nm laser line was used to generate the reflection signal from the refractile elemental sulfur granules with a detection window of 478–498 nm, while the autofluorescence from the purple sulfur bacterial cells was collected using the 543 nm laser line and automatic filter settings for Alexa546 fluorophore.

Sulfide consumption assay

Triplicate microcosms were established with 50 small berries each (~1–3 mm diameter) in 50 ml serum bottles of anoxic filter-sterilized in-situ marsh water under an N2/CO2……
headspace (90:10), with or without sulfide added to a final concentration of 1 mM. Triplicate abiotic controls with and without 1 mM sulfide were also established and contained only anoxic filter-sterilized in situ marsh water. Microcosms were incubated on a 14 h light/10 h dark cycle at 28°C, and soluble sulfide was monitored spectrophotometrically (Cline, 1969).

Cyclic microvoltammetry

Voltammetric analysis of berries collected in a 50 ml Falcon tube were performed utilizing glass Au-Hg amalgam electrodes (with tips drawn to ∼ 500 μm diameter) lowered vertically in 0.1–1 mm increments using a manual micromanipulator. The electrodes were constructed and calibrated according to the methods outlined by Brendel and Luther (1995). Electrodes were calibrated in the lab for O₂, HS⁻ and Mn²⁺ using water collected from the sample site; each electrode’s response was checked immediately before use by measuring the signal for 200 μM Mn²⁺ and calibrated using the pilot ion method after Meites (1965) and Slowey and Marvin-DiPasquale (2012). The tip of the electrode was positioned to penetrate a number of berries using this technique. The berries typically compressed slightly before the electrode tip was able to penetrate, followed by movement of the berry itself with the electrode as it penetrated. As such, exact spatial reference was not possible, although it was clear that a number of scans did occur inside individual berries. A sequence of 10 cyclic voltammograms was obtained at each position using a DLK-60 potentiostat and software (Applicational Instrument Systems, Flemington, NJ, USA). Instrumental variability between measurements was typically <1%. Sulfide was also independently measured in other aggregates using a Unisense sulfide microsensor (Unisense, Aarhus, Denmark) according to manufacturer’s instructions, with total sulfide calculated assuming an interior pH of 8 (Seitz et al., 1993).

Sulfide capture and SIMS 7f-Geo ion microprobe analysis of 34S

Large berries (0.5–1 cm diameter) were collected, rinsed free of sediment, threaded onto 24 gauge silver wire (99.95%; Surepure Chemetals, Florham Park, NJ, USA) and incubated in situ from 4 p.m. until 11 a.m. the next day. Berries were then removed, wires were rinsed with de-ionized water and stored under a nitrogen atmosphere prior to analysis. The wire was sectioned, mounted onto a glass round using double-sided carbon tape and sputter-coated with 10 nm of gold. Analysis of silver sulfide precipitated on metallic silver was conducted using the Cameca IMS 7f-Geo magnetic sector SIMS at the Caltech Center for Microanalysis using methods described previously (e.g. Fike and Grotzinger, 2008; Fike et al., 2008; Fike et al., 2009) and in detail in the Supporting Information S1.

Stable isotope amendment experiments

Anoxic, filter-sterilized in-situ marsh water was amended with 13C-enriched bicarbonate (98 atom % 13C, Isotec Sigma-Aldrich, St. Louis, MO, USA) at a 10 mM final concentration, and 34S-enriched sulfate (90 atom % 34S, Isotec Sigma-Aldrich) at a 28 mM final concentration, on top of the concentrations naturally present in the water (sulfate initially measured at 26.5 mM). Berries were washed free of sediment and placed into serum bottle incubations with sulfide added to 0.5 mM and an N₂/CO₂ (90:10) headspace. Incubations were maintained for 4 days at 28°C either in the dark, or the light (14 h light/ 10 h dark cycle). Similar light/dark incubations were also established in the presence of 10 mM of sodium molybdate to inhibit the activity of sulfate-reducing bacteria in the aggregates. Isotopically unlabelled light and dark control incubations were incubated in parallel and consisted of equivalent additions of standard isotopic composition bicarbonate and sulfate on top of that naturally present in the marsh water.

After 4 days, berries were removed from the incubations, fixed, embedded and sectioned for nanoSIMS analysis. Berries from the light condition were sectioned onto glass rounds and subsequently sputter-coated with 10 nm of gold. Continuous dark incubations were sectioned onto conductive ITO squares (Dekas and Orphan, 2011). Several berries from three dark biological replicates (+/− molybdate, and unlabelled controls) were fixed and flash frozen without embedding for analysis by bulk elemental analyser isotope ratio mass spectrometry (EA-IRMS).

NanoSIMS sample preparation and imaging

Samples for nanoSIMS analysis were optically mapped using phase contrast and epifluorescence microscopy to identify islands of PB-PSB1 target cells. Neither FISH nor CARD-FISH were conducted on these samples to preserve the intracellular elemental sulfur inclusions, which were found to wash out during permeabilization steps required for these protocols. Target PB-PSB1 cells were found to have abundant intracellular sulfur inclusions prior to nanoSIMS analysis.

Measurements were conducted on the Cameca NanoSIMS 50 L instrument at the Caltech Center for Microanalysis in two separate 3-day sessions in 2010 and 2011. Samples were collected using a primary Cs⁺ ion beam at 1.2 pA corresponding to a nominal spot size of ∼ 50 nm. The beam was rastered at either 256 × 256 or 512 × 512 pixel resolution over square regions from 15 to 30 μm in size. All samples were presputtered for 10–15 min to locally remove any exterior layers or gold coating. Seven secondary ions were simultaneously collected, ¹²C, ¹³C, ³²S⁻, ³⁴S⁻, ³¹P⁻, ³²S³⁴S⁻. NanoSIMS images were processed using ‘Open MIMS’, a plug-in to ImageJ available online at http://www.nrims .harvard.edu/NRIMS_ImageJ.php (Gormanns et al., 2012). Each series of frames was corrected for drift and detector dead time but represent raw values that were not corrected for instrumental mass fractionation. Values shown are the sum of several frames from each analysis region.

Bulk analysis of sulfur isotopes by EA-IRMS

Sulfate from in-situ marsh water was precipitated with barium chloride (Kolmert et al., 2000), dried and prepared for EA-IRMS. Pink berries preserved from triplicate incubations (dark, +/- isotope labels, +/- 10 mM sodium molybdate) were dried at 55°C for 48 h, and crimped in
Radiocarbon assay of carbon fixation

Incubations of five sediment-free 2 mm diameter berries were placed in small screw-cap tubes with 1 ml of filter-sterilized in-situ marsh water and an N₂/CO₂ headspace (90:10). Duplicate incubations were pre-equilibrated for 1 h in the ambient light, dark or with 10 mM of final concentration sodium molybdate. Duplicate vials were also prepared with heat-killed berries (10 min boil). Just before the start of the experiment, each incubation was amended with neutralized sulfide to a final concentration of 1 mM, followed by the addition of 10 μL of 13C bicarbonate in 0.01 M of sodium hydroxide with a nominal specific activity of 250 μCi/ml. Incubations were sampled after either 1 or 4 h at room temperature illuminated by an array of 196 infrared light emitting diodes (λ = 850 nm) to ensure that any observed carbon fixation came from the purple sulfur bacteria and not from oxygenic phototrophs (diatoms, cyanobacteria) in the berries.

Incubations were terminated by the addition of 1 ml of saturated urea solution and heating to 85°C for 30 min to inactivate and disaggregate the berries. Unincorporated radioactive bicarbonate was removed by heating 50 μL of this berry homogenate with 400 μL of glacial acetic acid in glass scintillation vials at 65°C for 20 min. Vials were gently tapped at 650 multipurpose scintillation counter (Beckman Coulter, Fullerton, CA, USA).

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References


Sulfur cycling in pink berries of the Sippewissett Marsh


Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher’s web-site:

S1. Supplemental results and discussion.
S2. Supplemental data. SIMS 7f-GEO raw and processed data used to construct for main text Figure 7C,D.
S3. Supplemental data. NanoSIMS-50L raw and processed data used to construct Figure 8A,B in main text.

Fig. S1. Maximum-likelihood phylogeny (rooted) constructed from 16S rRNA gene sequences of pink berry purple sulfur bacteria PB-PSB1 and cultured Chromatiales relatives. Phylogeny was constructed with FastTree using the approximate maximum-likelihood method (Price et al., 2010) and GTRCAT approximation with 20 rate categories. Values at the nodes are SH-like local supports (1000) computed by FastTree and used as confidence values of tree branches. Scale bar represents the number of estimated changes per position for a unit of branch length.

Fig. S2. Maximum-likelihood phylogeny (mid-point rooted) constructed from 16S rRNA gene sequences of pink berry Bacteroidetes phylotypes OTUs (pink), cultured isolates (blue) and uncultured environmental amplicons. Phylogeny was constructed with FastTree using the approximate maximum-likelihood method (Price et al., 2010) and GTRCAT approximation with 20 rate categories. Values at the nodes are SH-like local supports (1000) computed by FastTree and used as confidence values of tree branches. Scale bar represents the number of estimated changes per position for a unit of branch length. Marked with red stars are the dominant pink berry phylotypes. Note the relative scarcity of cultured isolates and abundance of related sequences from diverse sulfur-cycling habitats.

Fig. S3. Maximum-likelihood phylogeny (mid-point rooted) constructed from 18S rRNA gene sequences of pink berry eukaryotes OTUs and cultured relatives. Phylogeny was constructed with FastTree using the approximate maximum-likelihood method (Price et al., 2010) and GTRCAT approximation with 20 rate categories. Values at the nodes are SH-like local supports (1000) computed by FastTree and used as confidence values of tree branches. Scale bar represents the number of estimated changes per position for a unit of branch length.
Fig. S4. Epifluorescence microscopy of CARD-FISH hybridization of sectioned pink berries with a nonsense probe (NON338, panel A), and a Gammaproteobacteria probe (GAM42a, panel B). The left side of each panel shows the Alexa 488 probe signal and background autofluorescence; the right side of the panel shows the DAPI stain.

Fig. S5. Maximum-likelihood phylogeny (FastTree) constructed from an alignment of full-length dsrAB gene sequences (Loy et al., 2009). Illumina sequence reads were processed with the Phylosift pipeline which placed them onto this fixed, full-length reference tree using pplacer (Matsen et al., 2010). Branches with reads placed are in red, and with a branch line width proportional to the number of assigned sequences.

Fig. S6. Chromatiales soxYZ gene. Generated by RAST synteny viewer using 1e-20 BLASTP similarity cut-off to define and colour gene sets (each set has unique number and colour). Ordered according to % aa similarity to scaffold_341 soxY query. Note the conserved Chromatiales hypothetical gene cluster upstream from soxYZ (7,12,10,3).

Fig. S7. Chromatiales dsrABEFHMKLJOPNRS gene cluster is represented in three distinct metagenomic contigs from PB-PSB1. Generated by RAST synteny viewer using 1e-20 BLASTP similarity cut-off to define colour gene sets (each set has unique number and colour). Ordered according to % aa similarity to scaffold_285 dsrA query. Genes shown in parenthesis at top (dsrH and dsrJ) were not annotated on metagenomic contigs by RAST but are identifiable as gene fragments using independent BLASTP queries. Also, note the conserved Chromatiales hypothetical gene cluster upstream from dsrAB (10,17,16/18).

Fig. S8. Genomic context of aprM–aprBA gene cluster in PB-PSB1. Generated by RAST synteny viewer using 1e-20 BLASTP similarity cut-off to define and colour gene sets (each set has unique number and colour). Ordered according to % aa similarity to the scaffold_71 aprB query.

Fig. S9. Genomic context of aprAB–qmoABC gene cluster in PB-SRB1. Generated by RAST synteny viewer using 1e-20 BLASTP similarity cut-off to define and colour gene sets (each set has unique number and colour). Ordered according to % aa similarity to the scaffold_149 aprA query.

Table S1. Quantification of the single copy phylogenetic marker genes for estimating genome completion and number of genomes per bin of the PB-SRB1 and PB-PSB1 associated bins. Note that translation elongation factor EF-2 is duplicated in the closely related Desulfobulbaceae genomes.

Table S2. Genes of interest in the PB-PSB1 and PB-SBR1 genomes. Gene locations are based on the RAST annotations of the genomes (complete dataset available at FigShare).