Dissulfurirhabdus thermomarina gen. nov., sp. nov., a thermophilic, autotrophic, sulfite-reducing and disproportionating deltaproteobacterium isolated from a shallow-sea hydrothermal vent

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A thermophilic, anaerobic, chemolithoautotrophic bacterium, strain SH388T, was isolated from a shallow, submarine hydrothermal vent (Kuril Islands, Russia). Cells of strain SH388T were Gram-stain-negative short rods, 0.2–0.4 µm in diameter and 1.0–2.5 µm in length, and motile with flagella. The temperature range for growth was 25–58 °C (optimum 50 °C), and the pH range for growth was pH 5.0–7.0 (optimum pH 6.0–6.5). Growth of strain SH388T was observed in the presence of NaCl concentrations ranging from 0.5 to 4.0 % (w/v) (optimum 2.0–2.5 %). The strain grew chemolithoautotrophically with molecular hydrogen as electron donor, sodium sulfite as electron acceptor and bicarbonate/CO2 as a carbon source. It was also able to grow by disproportionation of sulfite and elemental sulfur but not thiosulfate. Sulfate, Fe(III) and nitrate were not used as electron acceptors either with H2 or organic electron donors. Phylogenetic analysis based on 16S rRNA gene sequences indicated that the isolate belonged to the class Deltaproteobacteria and was most closely related to Dissulfuribacter thermophilus and Dissulfurimicrobium hydrothermale (91.6 % and 90.4 % sequence similarity). On the basis of its physiological properties and results of phylogenetic analyses, strain SH388T is considered to represent a novel species of a new genus, for which the name Dissulfurirhabdus thermomarina gen. nov., sp. nov. is proposed. The type strain of the species is SH388T (=DSM 100025T=VKM B-2960T). It is the first thermophilic disproportionator of sulfur compounds isolated from a shallow-sea environment.

Chemolithoautotrophic micro-organisms can gain energy from a variety of inorganic compounds serving as electron donors and acceptors. Sulfur dioxide is one of the most typical and abundant volcanic gases. It is highly soluble in water; thus, in aquatic environments, including hydrothermal vents, SO2 is usually present in the form of sulfite ions. Micro-organisms capable of dissimilatory sulfite reduction are phylogenetically diverse and include all sulfate-reducers as well as many nonsulfate-reducing species. Overall, the ability to use sulfite as an electron acceptor with organic or inorganic electron donors is known for representatives of the bacterial phyla Firmicutes, Proteobacteria, Nitrospirae and Thermodesulfovibacteria and for archaea of the phyla Crenarchaeota and Eur-yarchaeota (Simon & Kroneck, 2013; Slobodkin et al., 1999). Some sulfite-reducers are also capable of sulfite disproportionation. Growth coupled to disproportionation of sulfite...
was reported for mesophilic representatives of the deltaproteobacterial genera Desulfovibrio, Desulfoascapaa, Desulfonatronum, Desulfonatronospira and Desulfonatronovibrio (Bak & Pfennig, 1987; Finster et al., 1998; Janssen et al., 1996; Pikuta et al., 2003; Sorokin et al., 2008, 2011) as well as for two thermophiles, Dissulfuribacter thermophilus and Dissulfuririmicobium hydrothermale (Slobodkin et al., 2013, 2016). Beyond the class Deltaproteobacteria, this ability is known for only one species, Thermosulfurimonas dismutans, belonging to the phylum Thermodesulfobacteria (Slobodkin et al., 2012). Here we report the isolation and characterization of a novel chemolithotrophic, thermophilic, sulfite-reducing and disproportionating bacterium from a shallow-sea hydrothermal vent.

Strain SH388<sup>T</sup> was isolated from a mixed sample of sand, hydrothermal fluid (thermal water and dissolved gases) and seawater collected at a shallow, submarine hydrothermal vent located at a depth of 12 m and at 200–250 m offshore (Kunashir Island, Kurils, Russia). Temperature and pH at the sampling site (44°29.469′N 146°06.247′E) varied within the range 60–84 °C and pH 6.0–6.5, respectively. Samples were taken anaerobically in tightly stopped bottles and transported to the laboratory. An enrichment culture was initiated by inoculation of the sample (10 %, w/v) into anaerobically prepared, bicarbonate-buffered liquid medium of the following composition (per litre of distilled water): 0.33 g NH<sub>4</sub>Cl, 0.33 g KCl, 0.33 g CaCl<sub>2</sub>·6H<sub>2</sub>O, 0.33 g KH<sub>2</sub>PO<sub>4</sub>, 18.0 g NaCl, 4.33 g MgCl<sub>2</sub>·6H<sub>2</sub>O, 2.0 g NaHCO<sub>3</sub>, 1 ml trace element solution (Slobodkin et al., 2012) and 1 ml vitamin solution (Wolin et al., 1963). The isolation medium had a pH of 6.5–6.8 (measured at 25 °C). No reducing agents were added. The medium was dispensed in 10 ml portions into 17 ml Hungate tubes. If not mentioned otherwise, the gas phase consisted of H<sub>2</sub>/CO<sub>2</sub> (80:20, v/v). Sodium sulfite from a sterile stock solution was added as electron acceptor to a final concentration of 5 mM. A sterile, anoxic stock slurry of poorly crystalline Fe(III) oxide (ferrihydrite) was added to obtain a final concentration of 10 mmol Fe(III) l<sup>−1</sup>, as a scavenger of sulfide generated by sulfite reduction. The ferrihydrite was synthesized by titrating a solution of FeCl<sub>3</sub>·6H<sub>2</sub>O (60 g l<sup>−1</sup>) with NaOH (10%, w/v) to pH 8.0–9.0. After incubation of the enrichment at 50 °C for 15 days, ferrihydrite was converted to a black, non-magnetic, Fe(II)-containing precipitate, presumably FeS. After three subsequent transfers and following serial 10-fold dilutions in the same medium, only one morphological type of cells was observed in the highest growth-positive dilution (10<sup>−8</sup>). Attempts to obtain separate colonies were unsuccessful either with 1 % Gelrite gellan gum or with 1 % agar as solidifying agent in the medium with or without ferrihydrite. A pure culture of strain SH388<sup>T</sup> was obtained by means of multiple serial dilutions-to-extinction in the same liquid anaerobic medium. Light and electron microscopy, physiological studies on substrate and electron acceptor utilization, temperature, pH and salinity ranges for growth, analytical techniques for determination of metabolite products, determination of DNA G+C content and cellular fatty acids (CFA) composition were performed as described previously (Slobodkina et al., 2016). Genomic DNA of strain SH388<sup>T</sup> was extracted using the method of Marmur (1961) and purified using Wizard MaxiPreps DNA Purification Resin (Promega). 16S rRNA gene amplification and sequencing were done as described previously (Slobodkina et al., 2012). Pairwise similarity values were calculated by means of the EzTaxon server (http://www.ezbiocloud.net/eztaxon; Kim et al., 2012). Alignment with a representative set of related 16S rRNA gene sequences, evolutionary analysis and phylogenetic tree reconstruction were performed as described previously (Slobodkina et al., 2016).

Cells of strain SH388<sup>T</sup> were straight rods with rounded ends, 0.2–0.4 μm in diameter and 1.0–2.5 μm in length, growing singly or in pairs. Cells were motile due to a single polar flagellum (Fig. 1a). Formation of endospores was not observed. Ultrathin sections of strain SH388<sup>T</sup> revealed a Gram-negative cell wall type with an outer membrane (Fig. 1b). The temperature range for growth of strain SH388<sup>T</sup> was 25–58 °C with an optimum at 50 °C. No growth was detected at 26 or 60 °C after incubation for 3 weeks. The pH range for growth was pH 5.0–7.0, with optimum growth at pH 6.0–6.5. No growth was detected at pH 5.0 or 7.5. Growth of strain SH388<sup>T</sup> was observed at NaCl concentrations ranging from 0.5 to 4.0 % (w/v) with an optimum at 2.0–2.5 % (w/v), but no growth was evident below 0.4 or above 4.5 % (w/v) NaCl.

Strain SH388<sup>T</sup> grew lithoautotrophically with molecular hydrogen as an electron donor, sodium sulfite as an electron acceptor and bicarbonate/CO<sub>2</sub> as a carbon source. Sulfite could be replaced by SO<sub>2</sub> gas [SO<sub>2</sub>/CO<sub>2</sub> (15:85, v/v) in the gas phase] that resulted in growth with the same specific growth rate and final cell yield. Sulfite or SO<sub>2</sub> gas reduction was accompanied by hydrogen consumption and formation of hydrogen sulfide; the presence of ferrihydrite was not essential. In the absence of molecular hydrogen, strain SH388<sup>T</sup> grew by disproportionation of sulfite (5 mM), SO<sub>2</sub> gas [SO<sub>2</sub>/CO<sub>2</sub> (15:85, v/v) in the gas phase] and elemental

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Fig. 1. Cell morphology of strain SH388<sup>T</sup>. (a) Electron micrograph of negatively stained cells showing overall cell morphology and localization of the single flagellum. (b) Ultrathin section showing cell wall structure; CM, cytoplasmic membrane; OM, outer membrane. Bar, 0.2 μm.
sulfur (5 g l\(^{-1}\)), but not thiosulfate (15 mM). The growth was accompanied by accumulation of sulfate and conversion of ferrihydrite to black, non-magnetic precipitate, indicating the production of sulfide. For disproportionation of elemental sulfur, the presence of ferrihydrite was required; disproportionation of sulfate and SO\(_2\) gas could proceed without ferrihydrite. Addition of pyruvate, malate (10 mM each), glucose, fructose and sucrose (2 g l\(^{-1}\) each) to medium with sodium sulfite slightly increased the growth rate but did not increase the final cell number. Acetate, propionate, butyrate, formate, methanol, ethanol, n-propanol, i-propanol, lactate, fumarate, succinate, glycerol (10 mM each), peptone and yeast extract (2 g l\(^{-1}\) each) did not stimulate growth of strain SH388\(^T\) with sodium sulfite. The new isolate did not grow and did not reduce sulfate (15 mM), nitrate (10 mM) or ferrihydrite [90 mmol Fe(III) l\(^{-1}\)] with hydrogen [H\(_2\)/CO\(_2\) (80:20, v/v)], acetate, lactate, pyruvate, succinate, ethanol (10 mM each), and did not ferment these substances in anaerobic conditions. CFAs of strain SH388\(^T\) grown in medium with hydrogen and sulfite and harvested in the late exponential phase of growth comprised a mixture of saturated and monounsaturated straight-chain and branched fatty acids (Table S1, available in the online Supplementary Material). The major cellular fatty acids were i-C\(_{15}:0\) and C\(_{16}:0\) (32.4 and 23.2 % of the total, respectively) with lesser amounts of C\(_{18}:1\)\(^\Delta7\) (7.8 %), i-C\(_{17}:1\)\(^\Delta8\) (6.8 %), C\(_{17}:0\)\(^\Delta6\)

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(6.0 %) and C_{14:0} (5.7 %). Other fatty acids were present in low or trace amounts (<5 %). The G+C content of the genomic DNA of strain Sh388^T was 64.6 mol% (T_m).

A comparison of 1521 nt of 16S rRNA gene sequence of strain Sh388^T with those available in the GenBank and EzTaxon server databases showed that the strain belonged to the class Deltaproteobacteria (Fig. 2), displaying highest sequence similarity to Dissulfurirhabdus thermophilus S69^T (91.6 %) and Dissulfurimicrobium hydrothermale Sh68^T (90.4 %) and being distantly related (less than 88.6 % 16S rRNA gene sequence similarity) to the species of the orders Syntrophobacterales, Desulfobacterales and Desulfothermoanales.

Strain SH388^T was isolated from a shallow-sea hydrothermal vent where it participates in biogeochemical cycling of sulfur, most probably as a primary producer. It is the first thermophilic disproportionator of sulfur compounds isolated from a shallow-sea environment to our knowledge. SH388^T shares the distinctive physiological features of the most closely related species—the ability to disproportionate sulfur compounds at elevated temperatures, combined with the inability to accomplish dissimilatory sulfate reduction. In addition to significant phylogenetic distance, strain SH388^T differs from related strains in genomic DNA G+C content, CFA profile and in some physiological characteristics, including Fe(III) reduction and thiosulfate utilization (Table 1). On the basis of phylogenetic position and phenotypic properties, we propose to classify strain SH388^T as the type strain of a novel species of a new genus in the class Deltaproteobacteria, Dissulfurirhabdus thermomarina gen. nov., sp. nov.

**Description of Dissulfurirhabdus thermomarina gen. nov.**

Dissulfurirhabdus (Dis.sul.fi.ru.hab’ dus. L. inseparable particle dis in two; L. n. sulfur sulfur; Gr. fem. n. rhabdos, rod; N.L. fem. n. Dissulfurirhabdus, a rod that disproportionates sulfur).

Cells are rod-shaped. Cell wall of Gram-negative type. Thermophilic. Anaerobic. Neutrophilic. Do not form endospores. Chemolithoautotrophic growth by reduction or disproportionation of sulfur compounds. Member of the class Deltaproteobacteria. The type species is Dissulfurirhabdus thermomarina.

**Description of Dissulfurirhabdus thermomarina sp. nov.**

Dissulfurirhabdus thermomarina (ther.mo. ma.ri’na. Gr. adj. ther.mos warm; hot; L. fem. adj. marina of the sea, marine; N.L. fem. adj. ther momarina warm and marine, referring to the site of isolation).

Has the following properties in addition to those given in the description of the genus. Cells are straight rods, 0.2–0.4 µm in diameter and 1.0–2.5 µm in length, growing singly or in pairs. Cells are motile with a single polar flagellum. Gram-stain-negative. Thermophilic. Growth occurs at 25–58 °C (optimum at 50 °C), pH 5.0–7.0 (optimum pH 6.0–6.5) and NaCl concentrations of 0.5–4.0 % (w/v) (optimum 2.0–2.5 %, w/v NaCl). Grows chemolithoautotrophically using hydrogen as an electron donor, sulfite or SO_2 gas as an electron acceptor and bicarbonate/CO_2 as a carbon source. Able to grow by disproportionation of sulfate, SO_2 and elemental sulfur with sulfide and sulfate formation. Does not reduce sulfate, nitrate or ferrihydrite with hydrogen, acetate, lactate, pyruvate, succinate, ethanol or peptone. Does not oxidize elemental sulfur or thiosulfate with nitrate or oxygen. Does not grow aerobically with acetate, pyruvate, succinate, glucose, fructose, maltose, sucrose, arabinose and peptone and does not ferment them.

The type strain, SH388^T (=DSM 100025^T=VKM B-2960^T), was isolated from a shallow, submarine hydrothermal vent

**Table 1. Characteristics that distinguish strain SH388^T from representatives of the most closely related species**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of isolation</td>
<td>Shallow-sea hydrothermal vent</td>
<td>Deep-sea hydrothermal vent</td>
<td>Terrestrial hydrothermal pond</td>
</tr>
<tr>
<td>Temperature range (°C)</td>
<td>25–58</td>
<td>28–70</td>
<td>30–65</td>
</tr>
<tr>
<td>Temperature optimum (°C)</td>
<td>50</td>
<td>61</td>
<td>50–52</td>
</tr>
<tr>
<td>pH range</td>
<td>5.0–7.0</td>
<td>5.6–7.9</td>
<td>5.2–7.5</td>
</tr>
<tr>
<td>pH optimum</td>
<td>6.0–6.5</td>
<td>6.8</td>
<td>6.0–6.2</td>
</tr>
<tr>
<td>NaCl (% w/v) range</td>
<td>0.5–4.0</td>
<td>0.9–5.0</td>
<td>0–2.3</td>
</tr>
<tr>
<td>Fe(III) reduction</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>S\textsubscript{2}O\textsubscript{3}\textsuperscript{2–} disproportionation</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Growth on H\textsubscript{2}S\textsubscript{O}\textsubscript{3}\textsuperscript{2–}</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Growth stimulation by:</td>
<td>Pyruvate, malate, glucose, fructose, sucrose</td>
<td>Fumarate, maleinate</td>
<td>Succinate</td>
</tr>
<tr>
<td>Major CFAs</td>
<td>i-C\textsubscript{15:0} and C\textsubscript{16:0}</td>
<td>C\textsubscript{18:1} v½, C\textsubscript{16:1} and cyc-C\textsubscript{19:0}</td>
<td>C\textsubscript{16:0}, cyc-C\textsubscript{19:0}, C\textsubscript{18:1} v½ and C\textsubscript{18:0}</td>
</tr>
<tr>
<td>DNA G+C content (mol%)</td>
<td>64.6</td>
<td>40.3</td>
<td>49.0</td>
</tr>
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</table>
(Kuril Islands, Russia). The DNA G+C content of the type strain is 64.6 mol% ($T_m$).

**Acknowledgements**

This work was supported by the grant 14-24-00165 from the Russian Science Foundation (autophagy) and by grant 15-04-00405 from the Russian Foundation for Basic Research (sulfur metabolism). CFA determination was supported by President of Russia (grant MK-4530.2015.4). We thank N. A. Kostrikina (INM RAS) for the help with the electron microscopy of the new organism.

**References**


