Desulforegula conservatrix gen. nov., sp. nov., a long-chain fatty acid-oxidizing, sulfate-reducing bacterium isolated from sediments of a freshwater lake

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A novel sulfate-reducing bacterium, strain Mb1Paᵀ, was isolated from the sediments of a freshwater floodplain lake. Cells of strain Mb1Paᵀ were rod-shaped, 1–1.3 µm wide and 2.6–3 µm long, motile and Gram-negative. The bacterium grew on straight-chain carboxylic acids with 4–17 carbon atoms. Electron donors with an even number of carbon atoms were oxidized to acetate and electron donors with an odd number of carbon atoms were oxidized to acetate and propionate. No other compounds were found to be used as electron donors. No growth occurred in the absence of sulfate. The optimum temperature for growth was between 25 and 30 °C and the maximum temperature for growth was 32 °C. Strain Mb1Paᵀ grew very slowly in medium with 5 g NaCl l⁻¹ with optimum growth occurring with up to 10 g NaCl l⁻¹.

Analysis of the 16S rRNA gene showed that strain Mb1Paᵀ belonged to the δ-subclass of the Proteobacteria, was a member of the family Desulfobacteraceae, but lacked similarity with any currently described representatives. The combined phylogenetic analysis and physiological data indicate that strain Mb1Paᵀ represents a new genus and the name Desulforegula conservatrix is proposed. The type strain is Mb1Paᵀ (≡ DSM 13527ᵀ = ATCC BAA-134ᵀ).

Keywords: Desulforegula conservatrix, sulfate-reducing bacteria, long-chain fatty acids, sediment

INTRODUCTION

Widdel (1980) carried out a major study on sulfate-reducing bacteria (SRB) and described a diverse range of SRB that could use a variety of fatty acids as carbon and energy sources. In particular, enrichment cultures containing hexadecanoate yielded several previously undescribed strains of SRB which were described as Desulfovibrio sapovorans. More recently, phylogenetic studies transferred the latter organisms to the genus ‘Desulfobotulus’ (Widdel & Bak, 1992). Further studies have since been carried out that have attempted to extend our knowledge of compounds that can be oxidized by SRB. Such studies have demonstrated that compounds as diverse as alkanes (Ackersberg et al., 1991; Reuter et al., 1994), amino acids (Rees et al., 1998), and variously substituted aromatic compounds (Drzyzga et al., 1993; Rabus et al., 1993; Schnell & Schink, 1992) can be oxidized by SRB. Despite the early interest into SRB that oxidize long-chain fatty acids (Widdel, 1980), the more recent studies involving SRB able to use long-chain fatty acids have been limited to carbon and electron donor tests performed on isolates obtained by enrichment with alternative substrates. As yet unidentified strains known to be able to degrade long-chain fatty acids have been isolated from marine or estuarine sediments (Widdel & Bak, 1992), but freshwater environments have been less extensively examined. In this study, we examined sediments from a freshwater wetland lake for SRB able to oxidize hexadecanoate. Rather than isolating ‘Desulfobotulus sapovorans’, enrichment led to the isolation of a previously undescribed organism. In this

Abbreviation: SRB, sulfate-reducing bacteria.
The GenBank accession number for the 16S rRNA sequence of strain Mb1Paᵀ is AF243334.
paper, we describe the isolation and characterization of strain $\text{Mb1Pa}^T$.

METHODS

Isolation and culture conditions. Strain $\text{Mb1Pa}^T$ was isolated by enrichment from the sediment of a wetland lake that is on the floodplain of the River Murray, Albury, Australia. Primary enrichment cultures contained approximately 1 g sediment in 10 ml medium that had been supplemented with 1 mM sodium palmitate. Palmitate continued to be supplied as the electron donor throughout the enrichment stages but was replaced with butyrate for final purification by agar shake dilution tubes. Dilute freshwater medium (Janssen et al., 1997) preparation and anaerobic culture techniques were used throughout this study, with all media prepared as described previously (Rees et al., 1995). Substrates and electron acceptors were added as required from sterile stock solutions. All incubations were carried out at 25 °C. When necessary, Desulfovibrio desulfuricans DSM 642 was used as a control for growth experiments.

Cellular and metabolic characterization. Desulfoviridin was determined by the fluorescence test (Postgate, 1959) but with the fluorescence detection carried out with a fluorescence spectrophotometer. The pellet from 30 ml culture was washed and resuspended in 2 ml phosphate buffer (50 mM, pH 7). Following addition of 2 drops 2 M NaOH, the suspension underwent UV excitation in a Hitachi F4500 spectrophotometer and an emission spectrum was obtained from 500 to 800 nm. The presence of desulfoviridin was demonstrated by a single large peak with an emission maximum at 712 nm. The lipid nature of cell inclusions was demonstrated by staining with Nile blue (Ostle & Holt, 1982). Organic acids were determined by GC as described previously (Rees et al., 1997). Dry mass measurements were carried out as described previously (Rees et al., 1994).

DNA base composition and phylogenetic analysis. For phylogenetic studies, genomic DNA was purified from strain $\text{Mb1Pa}^T$ by the methods described by Ausubel et al. (1997). The universal primers Fd1 and Rd1 were used to obtain a PCR product of approximately 1.5 kb corresponding to base positions 1–1542 based on Escherichia coli numbering of the 16S rRNA gene (Winker & Woese, 1991) using procedures described previously (Redburn & Patel, 1993; Andrews & Patel, 1996). PCR products were sequenced using the ABI PRISM Dye Terminator Cycle Sequencing Kit containing AmpliTaq FS DNA polymerase and using an ABI 373A sequencer. A 10 µl reaction contained 35 ng PCR product, 4 µl cycle sequencing reaction mix, 3.2 pmol primer (Andrews & Patel, 1996) and 2.5 µg BSA. Thermal cycling was carried out using a Rapid Cycler (Idaho Technology) at a temperature transition slope of 2, an initial denaturation of 94 °C for 15 s, then 25 cycles of denaturation at 94 °C for 0 s, annealing at 50 °C for 10 s, and extension at 60 °C for 3 min.

The new sequence data that were generated were aligned, and an almost full-length consensus 16S rRNA gene sequence was assembled and manually checked for accuracy using the alignment editor ae2 (Maidak et al., 2000). These sequences were compared with others in the GenBank database (Benson et al., 2000) using BLAST (Altschul et al., 1997), to determine if any newly released closely related sequences existed in the database. For analysis, the sequences of Desulfosporosinus oceaneuse, Desulfosporosinus fragile, Desulfosphaera gelida, Desulfobacterium phenolicum, strain R-

RESULTS AND DISCUSSION

Morphological and physiological characteristics

Primary enrichment cultures with palmitate and lake sediment appeared to be totally dominated by rod-shaped cells. A pure culture was subsequently obtained and designated strain $\text{Mb1Pa}^T$. Cells of strain $\text{Mb1Pa}^T$ were rod-shaped, 1–1.3 µm wide and 2.6–3.3 µm long (Fig. 1). Motile cells were observed in early growth phases but at less frequency in older cultures. Cells

Fig. 1. Phase-contrast photomicrograph of Desulforegula conservatrix strain $\text{Mb1Pa}^T$. Bar, 10 µm.
stained Gram-negative and spores were not observed in any cultures. Cellular inclusions could be stained with Nile blue, indicating that the inclusion bodies were poly-3-hydroxybutyrate.

When growing under optimal conditions with 10 mM butyrate, subcultures (1%, v/v, inoculum) from an early stationary phase culture usually reached a maximum cell yield within 3–4 d. However, when cultures were stored for more than 4 weeks, subsequent subcultures had lag periods that were often greater than 1 week. The lag period could be reduced by including dithionite in the medium to give 100 µM final concentration.

Although strain Mb1PaT was isolated with a dilute salts medium, it grew equally well in standard freshwater medium containing 1 g NaCl l⁻¹ (Widdel & Bak, 1992). Growth occurred in medium with 5 g NaCl l⁻¹ but cultures required incubation for 2 weeks before measurable growth occurred. Strain Mb1PaT grew with an incubation temperature up to 32 °C, with optimum growth occurring at between 25 and 30 °C. A vitamin supplement was required for growth. Yeast extract could not replace the vitamin supplement.

The compounds that were used as electron donors by strain Mb1PaT were (mM): butyrate (5), valerate (5), hexanoate (5), octanoate (1), decanoate (0.25), dodecanoate (0.25), hexadecanoate (1) and heptadecanoate (1). Compounds not used by strain Mb1PaT were: lactate (10), pyruvate (10), malate (5), succinate (5), fumarate (5), ethanol (10), formate (5), formate (5) plus acetate (1), acetate (10), propionate (5), octadecanoate (1), glucose (5), benzoate (5) and citrate (5). Growth on decanoate occurred only when the concentration in the medium was no greater than 0.25 mM; growth was confirmed following additions of very small amounts of decanoate to cultures over time. The presence of 1.0 mM decanoate was sufficient to completely inhibit growth on butyrate.

Stoichiometric measurements demonstrated that the oxidation of 7.99 mmol butyrate l⁻¹ yielded 14.17 mmol acetate l⁻¹ and 47 mg dry mass of cells l⁻¹. These data represent a carbon recovery of 94.6%. When strain Mb1PaT oxidized valerate, acetate and propionate were produced in equimolar amounts. The oxidation of heptadecanoic acid resulted in an acetate to propionate ratio of 7. These stoichiometry studies are consistent with the incomplete oxidation of fatty acids as described by Widdel (1980). Strain Mb1PaT was unable to ferment pyruvate, fumarate or malate. Sulfit, thiosulfate or nitrate were not used as terminal electron acceptors.

All attempts to isolate DNA for base composition studies failed. Cells were easily lyzed; however, all subsequent procedures to isolate sufficient quantities of DNA, whether from original protocols or modification methods, failed. Cells contained desulfoviridin.

Phylogenetic analysis and taxonomic affiliation

Phylogenetic analysis showed that strain Mb1PaT was a member of the δ-subclass of the Proteobacteria and formed a new branch within the proposed family Desulfobacteraceae. The 16S rRNA gene sequence of Mb1PaT was not highly similar to any sequence in public databases. Instead, there were four strains with similarity between 89.4 and 89.9%. The most closely related organisms in the molecular database were strain R-Capr Al (89.9% similarity), Desulfotofaba gelida (89.9% similarity), Desulfobacterium indolicum (89.6% similarity) and Desulfonema limicola (89.4% similarity) (Fig. 2).
Strain Mb1Pa\textsuperscript{T} oxidized long-chain fatty acids, a trait which is in common with isolates obtained from a variety of sediment types. For example, ‘Desulfo\-botulus sapovorans’ was isolated from mud of a ditch in a dairy pasture (Widdel, 1980). In addition to ‘Desulfo\-botulus sapovorans’, Widdel (1980) also described two further strains, 2pa3 and 3pa8, that also were able to oxidize straight-chain fatty acids with 4–18 carbon atoms. Also, an uncharacterized oval-shaped organism that was able to oxidize long-chain fatty acids was referred to by Widdel (1988). Strain Mb1Pa\textsuperscript{T} has been isolated from brackish and marine environments whereas strain Mb1Pa\textsuperscript{T} was obtained from freshwater sediment. Desulfonema spp. are conspicuous filamentous SRB that exhibit gliding motility (Widdel \textit{et al}., 1983). Sequence comparison showed a relatively distant relationship to Desulfonema limicola. Similarly, significant morphological and physiological differences were observed between these two organisms (Table 1). Given the distance from the nearest relatives, combined with the physiological differences with any related organisms, we propose that strain Mb1Pa\textsuperscript{T} represents a new species of a new genus. We propose the name Desulfuregula conservatrix gen. nov., sp. nov.

### Table 1. Summary of morphological and physiological characteristics of strain Mb1Pa\textsuperscript{T} and related SRB

(+) Weak growth; NR not reported.

<table>
<thead>
<tr>
<th></th>
<th>Desulfuregula conservatrix strain Mb1Pa\textsuperscript{T}</th>
<th>Desulfobacte-rium indolicum strain In04\textsuperscript{†}</th>
<th>Desulfonema limicola strain 5ac10\textsuperscript{‡}</th>
<th>‘Desulfo-botulus sapovorans’ strain 1pa3\textsuperscript{§}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morphology</strong></td>
<td>Rod shaped</td>
<td>Rod-shaped</td>
<td>Filamentous</td>
<td>Vibrio</td>
</tr>
<tr>
<td><strong>Cell size (µm):</strong></td>
<td>Width: 1–1\textsuperscript{3}</td>
<td>Width: 0–1–1\textsuperscript{5}</td>
<td>Width: 2–2–1–1\textsuperscript{5}</td>
<td>Width: 1–1\textsuperscript{5}</td>
</tr>
<tr>
<td></td>
<td>Length: 2–6–3</td>
<td>Length: 2–2–6–2</td>
<td>Length: 2–2–6–2</td>
<td>Length: 1–1</td>
</tr>
<tr>
<td><strong>Motility</strong></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Oxidation of substrate</strong></td>
<td>Incomplete</td>
<td>Complete</td>
<td>Complete</td>
<td>Incomplete</td>
</tr>
<tr>
<td><strong>Electron donors used:</strong></td>
<td>\textit{H}_2, –</td>
<td>(+)</td>
<td>(+)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Formate, –</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Acetate, –</td>
<td>(+)</td>
<td>(+)</td>
<td>–</td>
</tr>
<tr>
<td><strong>Fatty acids (C atoms):</strong></td>
<td>4–17</td>
<td>4–4</td>
<td>3–14</td>
<td>3–14</td>
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<tr>
<td></td>
<td>Lactate, –</td>
<td>–</td>
<td>–</td>
<td>+</td>
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<tr>
<td></td>
<td>Fumarate, –</td>
<td>(+)</td>
<td>(+)</td>
<td>–</td>
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<tr>
<td></td>
<td>Ethanol, –</td>
<td>(+)</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>Ferment pyruvate, –</td>
<td>NR</td>
<td>–</td>
<td>+</td>
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<tr>
<td><strong>Electron acceptors used:</strong></td>
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<td>–</td>
<td>+</td>
<td>+</td>
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<tr>
<td></td>
<td>Thiosulfate, –</td>
<td>–</td>
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<td>+</td>
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<tr>
<td></td>
<td>Sulfur, –</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>Desulfoviridin, +</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

‡ Knoblauch \textit{et al}., 1999.
† Bak & Widdel (1986).
‡ Widdel \textit{et al}., 1998.
Description of Desulforegula gen. nov.

*Desulforegula* (De.sul.fo.re'gu.la. L. pref. de from; L. n. sulfur sulfur; L. n. fem regula a straight piece of wood or ruler; N.L. fem. n. *Desulforegula* a sulfate-reducing bacterium shaped like a ruler).

Cells are Gram-negative, straight rods and can be motile. Strict anaerobes that use sulfate as a terminal electron acceptor. *Desulforegula* belongs to the δ-subclass of the Proteobacteria. The nearest relatives are *Desulfofaba*, *Desulfobacterium* and *Desulfonema*. The type species is *Desulforegula conservatrix*.

Description of Desulforegula conservatrix sp. nov.

*Desulforegula conservatrix* (con.ser.va’trix. L. fem. n. conservatrix she who preserves, describing the storage of lipid cell inclusions).

Cells are rod-shaped, 1–1.3 µm wide and 2.6–3 µm long. The maximum temperature for growth is 32 °C, with optimum growth occurring between 25 and 30 °C. Optimum growth occurs with up to 1·0 g NaCl l⁻¹. Slow growth occurs in medium with 5 g NaCl l⁻¹. Oxidizes straight-chain carboxylic acids with 4–17 carbon atoms. No other substrates are known to be utilized. Substrates are incompletely oxidized. No growth occurs in the absence of sulfate. Habitat: sediment of freshwater lake. The type strain is MB1PaT (= DSM 13527T = ATCC BAA-134T).

ACKNOWLEDGEMENTS

This work was supported by the University of Canberra (grant 98/474) and the Cooperative Research Centre for Freshwater Ecology (Project B400). We thank Professor H. G. Trüper for assistance with the naming of the organism.

REFERENCES


