Clostridium caminithermale sp. nov., a slightly halophilic and moderately thermophilic bacterium isolated from an Atlantic deep-sea hydrothermal chimney

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A strictly anaerobic, slightly halophilic and moderately thermophilic, sporulating rod designated strain DVird3T was isolated from deep-sea hydrothermal vent samples collected at a depth of approximately 800 m on the Atlantic Ocean Ridge. Strain DVird3T possessed a few laterally inserted flagella, had a DNA G+C content of 33-1 mol% and grew optimally at pH 6-6 and at 45 °C. Growth was observed at temperatures between 20 and 58 °C and at pH values between 5-8 and 8-2. The optimum NaCl concentration for growth was 3 % sea salt (30 g l⁻¹); no growth was observed in the presence of 15 or 60 g sea salt l⁻¹. Strain DVird3T is heterotrophic and utilizes some sugars and various single amino acids. Acetate was the main fatty acid detected from carbohydrate fermentation, together with H₂ and CO₂. Gelatin was used as an energy source. It performed the Stickland reaction. Phylogenetically, strain DVird3T branched with members of cluster XI of the order Clostridiales, with Clostridium halophilum as its closest relative (similarity of 94-6 %). On the basis of its phenotypic, genotypic and phylogenetic characteristics, strain DVird3T (= DSM 15212T = CIP 107654T) is proposed as the type strain of a novel species of the genus Clostridium, Clostridium caminithermale sp. nov.

Deep-sea hydrothermal vents are inhabited by a wide range of microbial communities that comprise free-living microorganisms as well as micro-organisms living in association with invertebrates (Jeanthon, 2000). Among these free-living micro-organisms are bacteria belonging to the ε-subclass of the Proteobacteria, and the significance of their ecological role has been identified, mainly in molecular surveys (Haddad et al., 1995; Jeanthon, 2000; Reysenbach et al., 2000b; Corre et al., 2001). The recent isolation, from deep-sea hydrothermal vents, of moderately thermophilic and thermophilic members of the ε-subclass of the Proteobacteria has demonstrated the ability of these microorganisms to grow autotrophically using elemental sulfur as a terminal electron acceptor (Campbell et al., 2001; Alain et al., 2002a). This trait of sulfur reduction has also been found to be a common physiological feature of the well-studied, anaerobic, chemoautotrophic, thermophilic and hyperthermophilic micro-organisms (domain Archaea) isolated from these peculiar deep marine environments (Jeanthon, 2000). Besides chemoautotrophy and mixotrophy, chemoheterotrophy has also been recognized as a significant type of metabolism within the deep-sea hydrothermal vent anaerobic microbial community (Jeanthon, 2000). Among such trophic microbial groups inhabiting deep environments, little attention has been paid to anaerobic mesophiles and moderate thermophiles in comparison with thermophilic and hyperthermophilic micro-organisms from both domains (Bacteria and Archaea). Therefore, most microbiological studies performed so far have underlined the fact that thermophilic and hyperthermophilic archaea thrive in the hottest part of the ecosystem, with only a few thermophilic anaerobic members of the domain Bacteria being isolated (Jeanthon, 2000). The latter include members of the orders Thermotogales and Clostridiales. The order Clostridiales includes two thermophilic isolates: one, Caloranaerobacter azorenensis (Wery et al., 2001), is from the Atlantic rise hydrothermal vent; the other, Caminicella

The GenBank accession number for the 16S rRNA gene sequence of strain DVird3T is AF458779.
sporogenes (Alain et al., 2002b), is from the East-Pacific Rise hydrothermal vent. They respectively belong to clusters XII and XI of the Clostridium subphylum. Here, we report the isolation and characterization of a novel moderately thermophilic member of cluster XI of the Clostridium subphylum, originating from a deep-sea hydrothermal vent. We propose to assign this novel bacterium to a novel species of the genus Clostridium, Clostridium caminithermale sp. nov.

Samples of an active chimney from a North Atlantic Ocean deep-sea hydrothermal vent (Diva2 cruise, Menez Gwen site, 37°50′N, 31°31′W) were collected on 20 June 1994 at a depth of approximately 800 m, using the submarine Nautil. The samples were crushed anaerobically on board in sterile sea water in an anaerobic chamber. The resulting mud was transferred (i) into 50 ml serum vials closed with butyl rubber stoppers for storage at 4 °C, and (ii) into 1-8 ml cryotubes containing 90 µl DMSO as cryoprotectant for storage at −20 °C until processing. The Hungate technique (Hungate, 1969) was used throughout this study. The basal medium (BM) contained the following (1−1 distilled water): 1 g NH4Cl, 0.3 g KH2PO4, 0.3 g KH2PO4, 30 g sea salt (Sigma), 0.5 g cysteine hydrochloride, 1 mg resazurin (Sigma), 0.5 g peptone, 0.5 g yeast extract (Fisher Scientific) and 10 ml trace mineral element solution (Balch et al., 1979). The pH was adjusted to 7 with 10 M KOH. The medium was boiled under a stream of O2-free N2 gas and cooled to room temperature. Five-milliliter aliquots were dispensed into Hungate tubes and 20 ml aliquots were dispensed into serum bottles under a stream of N2/CO2 (80:20, v/v), and the sealed vessels were then autoclaved for 45 min at 110 °C. Prior to inoculation, Na2S.9H2O and NaHCO3 were injected from sterile stock solutions to respective final concentrations of 0·04 and 0·2 % (w/v). Enrichment was performed in 120 ml serum bottles. Xylan ‘oat spelt’ (2·5 g l−1) and xylan ‘birchwood’ (2·5 g l−1) were added to the BM as an electron donor, with thiosulfate (20 mM) as an electron acceptor. The serum bottles were each inoculated with 6 ml sample, corresponding to approximately 10 % (v/v) of the final liquid volume. The bottles were incubated at 50 °C in a controlled-temperature oven for 2–3 days. Isolation was performed in the same medium. Three enrichment series were performed before isolation.

Growth experiments were performed in duplicate, using Hungate tubes containing BM. For pH growth experiments, BM containing glucose (20 mM) was adjusted to different pH values by injecting NaHCO3 or Na2CO3 from 10 % (w/v) sterile anaerobic stock solutions and then incubated at 45 °C. The temperature range for growth was determined using the same medium and adjusted to the optimum pH for growth. For studies on sea-salt requirements, sea salt was weighed directly into Hungate tubes and BM without sea salt was adjusted at the optimum pH for growth and dispensed into tubes as described above. Tubes were incubated at 45 °C. The strain was subcultured at least once under the same experimental conditions prior to inoculation for growth experiments. The presence of spores was determined by microscopic examination of the culture at different phases of growth. For substrate-utilization tests, BM was used. The substrates were injected from stock solutions into Hungate tubes to a final concentration of 10 mM for amino acids (L-leucine was the only amino acid weighed directly into the Hungate tubes), 5 g l−1 for peptides and proteins and 20 mM for sugars, fatty acids and alcohols. To test for sulfur-containing electron acceptors, thiosulfate (20 mM), sulfate (20 mM), elemental sulfur (2 %) and sulfite (2 mM) were added to the growth medium. Nitrate (10 mM) and nitrite (10 mM) were also tested as potential electron acceptors. Light and electron microscopy were performed as described previously (Cayol et al., 1994). Growth was measured by inserting duplicate Hungate tubes directly into a model UV-160A spectrophotometer (Shimazu) and measuring the OD546. Hydrogen and fermentation products (alcohols, volatile and non-volatile fatty acids) were quantified as described previously (Fardeau et al., 1993). Amino acid concentrations were determined by HPLC (Moore et al., 1958). The G+C content of the DNA and DNA–DNA hybridization were determined at the Deutsche Sammlung von Mikroorganismen und Zellkulturen (DSMZ), Braunschweig, Germany, as described by Hernández-Eugenio et al. (2002).

The methods for the purification and extraction of DNA and the amplification and sequencing of the 16S rRNA gene have been described previously (Andrews & Patel, 1996; Love et al., 1993; Redburn & Patel, 1993). Samples were loaded onto an Applied Biosystems 373XL sequencer and run for 12 h on a 4·5 % denaturing acrylamide gel. Sequence data were imported into the sequence editor BioEdit version 5.0.9 (Hall, 1999); the base calling was examined and a contiguous consensus sequence was obtained for each isolate. The full sequence was aligned using the SEQUENCE ALIGNER program of the Ribosomal Database Project (RDP; Maidak et al., 2001). The consensus sequence was then adjusted manually to conform to the 16S rRNA secondary-structure model (Winker & Woese, 1991). A non-redundant BLAST search (Altschul et al., 1997) of the full sequence through GenBank identified its closest relative. Sequences used in the phylogenetic analysis were obtained from the RDP (Maidak et al., 2001) and GenBank (Benson et al., 1999). Positions of sequence and alignment ambiguity were omitted and the pairwise evolutionary distances based on 1263 unambiguous nucleotides were calculated using the method of Jukes & Cantor (1969). Dendrograms were constructed using the neighbour-joining method (Saitou & Nei, 1987). Confidence in the tree topology was determined by using 100 bootstrapped trees (Felsenstein, 1985).

Enrichment cultures were incubated at 50 °C for 1 week. Growth was regarded as positive on the basis of optical density. Microscopic examination of the enrichment culture revealed the presence of large rods. Brown, circular colonies, 1–2 mm in diameter, appeared after 3 days incubation at 50 °C in roll tubes containing basal agar medium. Single colonies were picked using the techniques developed by...
Hungate (1969), and the process of serial dilution in roll tubes was repeated at least twice to purify the cultures. Six rod-shaped bacteria were isolated, designated strains DVird1–DVird6. Analysis of partial 16S rRNA gene sequences (200 bp) of the six strains showed that they were closely related phylogenetically, with a degree of similarity close to 100 % (data not shown). Strain DVird3 was further characterized.

Strain DVird3 was a strictly anaerobic rod. The cells were 0.4–0.5 μm in width and 5–9 μm in length and occurred singly or in pairs. Cells were motile by means of a few laterally inserted flagella. Spore formation was induced in the presence of oxygen and vitamins. Spores were oval and subterminal (Fig. 1a). Electron microscopy of sections of strain DVird3 exhibited a thick, stratified, Gram-positive-type cell wall composed of three dense layers (two thick layers and a thinner middle layer) separated by two less dense spaces (Fig. 1b). Strain DVird3 was moderately thermophilic and grew at temperatures ranging from 20 to 58 °C, with an optimum at 45 °C. The isolate was slightly halophilic and grew in the presence of sea-salt concentrations ranging from 12 to 55 g l⁻¹, with an optimum at 30 g l⁻¹. Strain DVird3 was neutrophilic; the optimum pH for growth was 6.6 and growth occurred between pH 5.8 and 8.2. In optimal conditions (batch conditions), the OD₅₈₀ can reach 1.0.

Yeast extract was required for growth on sugars. Strain DVird3 fermented yeast extract, peptone, Bio-trypticase and Casamino acids into a mixture of volatile fatty acids (acetate, propionate, butyrate, isobutyrate, isovalerate). Fructose, galactose, glucose, glycerol, maltose, mannose and ribose were used as energy sources. Glucose was converted into acetate [1–2 mol (mol glucose consumed)⁻¹], butyrate [0–2 mol (mol glucose consumed)⁻¹], propionate [0–2 mol (mol glucose consumed)⁻¹] and H₂ + CO₂. Propionic acid was the only fatty acid detected from succinate fermentation, whereas acetate together with butyrate and propionate were end-products of pyruvate metabolism. The following substrates were not used: arabinose, cellobiose, lactose, mannitol, melibiose, raffinose, rhamnose, starch, sucrose, xylose, dulcitol, sorbitol, lactate, formate, acetate, propionate and H₂ + CO₂. Use of amino acids as energy sources is detailed in the species description below. Strain DVird3 performed the Stickland reaction, using isoleucine as electron donor and methionine or betaine as electron acceptors. Other properties are detailed in the species description. The G+C content of strain DVird3 was 33.1 mol% (HPLC).

16S rRNA sequence analysis revealed that strain DVird3 was a member of cluster XI of the Clostridium subphylum, Clostridium halophilum being its closest phylogenetic relative (94.6 % similarity). Fig. 2 presents a dendrogram generated by the neighbour-joining method (Felsenstein,
from the Jukes–Cantor evolutionary similarity matrix (Jukes & Cantor, 1969). DNA–DNA hybridization between strain DVird3\textsuperscript{T} and Clostridium halophilum showed 50.9% relatedness.

Both molecular and microbiological studies within deep-sea hydrothermal vent ecosystems have demonstrated the ecological significance of anaerobic and microaerophilic thermophilic to hyperthermophilic micro-organisms (domains Bacteria and Archaea), most of which are involved, in particular, in the reduction (anaerobes) or oxidation (micro-aerophiles) of elemental sulfur (Jeanthon, 2000; Alain et al., 2002a; Götz et al., 2002). Thermophilic microaerophiles are recognized as hydrogenotrophic bacteria belonging to the order Aquificales (Reysenbach et al., 2000a; Götz et al., 2002), but hydrogenotrophic anaerobic thermophiles have also been recovered from deep-sea hydrothermal environments (Jeanthon, 2000; Jeanthon et al., 1998; L’Haridon et al., 1998; Alain et al., 2002a). The latter include methanogens, sulfate-reducing bacteria, members of the \( \varepsilon \)-subclass of the Proteobacteria, and heterotrophic sulfur-reducers belonging to the domain Archaea. It is only recently that two heterotrophic thermophilic anaerobes belonging to the order Clostridiales have been isolated and characterized. Caloranaerobacter azorenensis (Wery et al., 2001), isolated from a chimney sample, was ascribed as a member of cluster XII of the order Clostridiales, while Caminicella sporogenes (Alain et al., 2002b), isolated from entire tube samples of Alvinella pompejana attached to small fragments of chimney rocks, was ascribed as a member of cluster XI of the same order as defined by Collins et al. (1994). Both micro-organisms are considered as thermophiles, growing at temperatures above 60°C.

The genus Clostridium, order Clostridiales, was first defined as containing Gram-positive, anaerobic, rod-shaped and spore-forming bacteria unable to carry out the dissimilatory sulfate reduction (Cato et al., 1986; Hippe et al., 1992), but the genus has been reassessed taxonomically on the basis of phylogenetic considerations (Cato & Stackebrandt, 1989; Collins et al., 1994; Lawson et al., 1993; Rainey & Stackebrandt, 1993; Rainey et al., 1993; Stackebrandt & Rainey, 1997). Most members of this genus are ubiquitous chemo-organotrophic micro-organisms that may use carbohydrates and/or proteinaceous compounds as energy sources (Cato et al., 1986; Hippe et al., 1992). Here, we report on the isolation and characterization of a novel member of cluster XI, order Clostridiales, unable to grow at 60°C and thus considered as a moderate thermophile. Similarly to most members of this cluster, strain DVird3\textsuperscript{T} is an anaerobic, spore-forming micro-organism that grows heterotrophically on carbohydrates, peptones and amino acids. A mixture of volatile fatty acids, including formate, acetate, propionate, butyrate, isobutyrate and isovalerate, together with \( \text{H}_2 \) and \( \text{CO}_2 \), was produced from peptone fermentation by this strain. Acetate was found to be the primary fatty acid produced from glucose metabolism, with butyrate and propionate being produced in minor amounts. The 16S rRNA gene sequence analysis of this isolate indicated that it has two halophiles, Clostridium halophilum (similarity of 95.1%) and Caminicella sporogenes (similarity of 91.8%), as its closest phylogenetic relatives, indicating that the halophilic character of these three bacteria is an important phenotype in the assembly of these bacteria in the same phylogenetic lineage within cluster XI of the order Clostridiales. Besides halophiles, this cluster also contains a few other extremophilic micro-organisms including moderate thermophiles and alkaliphiles. Strain DVird3\textsuperscript{T} differs from Clostridium halophilum (Fendrich et al., 1990) in terms of the range of sugars and amino acids used, and also in the ranges of temperature and NaCl concentration for growth (Table 1). In view of these phenotypic characteristics, Clostridium halophilum is a thermotolerant, moderately halophilic micro-organism, while strain DVird3\textsuperscript{T} is a moderately thermophilic, slightly halophilic micro-organism. Strain DVird3\textsuperscript{T} also differs from Clostridium halophilum in that its DNA has a higher G+C content (33.1 versus 26.9 mol%). In contrast to Caminicella sporogenes, strain DVird3\textsuperscript{T} did not grow at temperatures above 60°C, used a wider range of sugars, did not reduce elemental sulfur or thiosulfate, performed the Stickland reaction and also had DNA with a higher G+C content (33.1 versus 24.2 mol%) (Table 1). Strain DVird3\textsuperscript{T} therefore represents a distinct phenotypic and phylogenetic lineage within cluster XI. Taking its phenotypic and phylogenetic characteristics into account, we propose to assign strain DVird3\textsuperscript{T} as the type strain of a novel species of the genus Clostridium (family Clostridiaceae, order Clostridiales, cluster XI), Clostridium caminithermale sp. nov. Strain DVird3\textsuperscript{T} is the first representative of the genus Clostridium that originates from deep-sea hydrothermal vents, confirming the ubiquity of members of this genus across the planet.

The isolation of Clostridium caminithermale extends our knowledge of the bacterial diversity inhabiting deep-sea hydrothermal environments and suggests that, besides thermophilic and hyperthermophilic anaerobic and facultative anaerobic communities, moderately thermophilic communities must also be taken into consideration regarding the overall carbon cycle recovery in these deep ecosystems. This is also true for the moderately thermophilic hydrogenotrophic anaerobic bacteria that have recently been isolated from hydrothermal vents along the East-Pacific Rise and at the Guaymas basin (Campbell et al., 2001). Interestingly, in contrast to the two other isolates from deep-sea hydrothermal vents belonging to the order Clostridiales, Clostridium caminithermale did not reduce any sulfur-containing compounds, including thiosulfate and elemental sulfur (see below), indicating that sulfur reduction might not be a common physiological trait amongst the anaerobic thermophiles that inhabit this deep ecosystem.

**Description of Clostridium caminithermale sp. nov.**

*Clostridium caminithermale* (ca.mi.ni.ther.ma’le. L. n. caminus chimney; L. pl. n. thermae hot springs; N.L. neut.
adj. \textit{caminithermale} of a thermal chimney, describing the site of sampling.

Cells are strictly anaerobic rods, 0·4–0·5 × 5–9 μm, occurring singly or in pairs. Motile by a few laterally inserted flagella. Electron microscopy of sections of cells exhibits a thick, layered, Gram-positive-type cell wall composed of three dense layers (two thick layers and a middle thinner layer) separated by two less dense spaces. Grows at 20–58°C ( optimum 45°C). Grows in the presence of sea salt at 12–55 g l\(^{-1}\) ( optimum 30 g l\(^{-1}\)). The optimum pH for growth is 6–6, but growth occurs between pH 5–8 and 8–2. Heterotrophic. Yeast extract is required for growth on sugars. Ferments yeast extract, peptone, Bio-trypticase and Casamino acids into a mixture of volatile fatty acids. Fructose, galactose, glucose, glycerol, maltose, mannose and ribose are fermented primarily into acetate, butyrate, propionate and H\(_2\)+CO\(_2\). Succinate, fumarate and pyruvate are also fermented. The following substrates are not used: arabinose, cellobiose, lactose, mannitol, melibiose, raffinose, rhamnose, starch, sucrose, xylose, dulcitol, sorbitol, lactate, formate, acetate, propionate and H\(_2\)+CO\(_2\). The following amino acids are used as energy sources in the presence of yeast extract and peptone (0·5 g l\(^{-1}\)): arginine, cysteine, glycine, proline and tyrosine (oxidized to acetate); glutamic acid (to propionate); histidine (to propionate and formate); isoleucine (to methyl 2-butyrate); leucine (to isovalerate); lysine (to acetate and butyrate); and methionine (to propionate and acetate). The following amino acids are not used: alanine, asparagine, aspartic acid, glutamine, phenylalanine, serine, threonine, tryptophan and valine. Performs the Stickland reaction, using isoleucine as electron donor and methionine or betaine as electron acceptors. Does not use elemental sulfur, sulfate, thiosulfate, sulfite, nitrate or nitrite as an electron acceptors. The following tests were negative: β-galactosidase, arginine dihydrolase, lysine and ornithine decarboxylases, Simmons’ citrate, H\(_2\)S production, urease, tryptophan deaminase, indole and acetoin production (Voges–Proskauer reaction). Adverse effects on animals and humans are not known. Because of the ability to degrade amino acids and peptides, the possibility of harmful effects cannot be excluded. Cautious handling and autoclaving of cultures before disposal is recommended. The G+C content of the type strain is 33–1 mol% (HPLC).

The type strain, strain DVird3\(^T\) (= DSM 15212\(^T\) = CIP 107654\(^T\)), was isolated from an Atlantic Ocean hydrothermal chimney.

### Table 1. Characteristics that differentiate strain DVird3\(^T\) from its closest relatives

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Strain DVird3(^T)</th>
<th>\textit{Clostridium halophilum}</th>
<th>\textit{Caminicella sporogenes}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gram type</td>
<td>Positive</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Temperature for growth (°C):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>20–58</td>
<td>18–49</td>
<td>45–65</td>
</tr>
<tr>
<td>Optimum</td>
<td>45</td>
<td>41</td>
<td>55–60</td>
</tr>
<tr>
<td>pH for growth:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>5–8–8·2</td>
<td>6–0–8·0</td>
<td>4·5–8·0</td>
</tr>
<tr>
<td>Optimum</td>
<td>6·6</td>
<td>7·4</td>
<td>7·5–8·0</td>
</tr>
<tr>
<td>Sea-salt concentration for growth (g l(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>&gt; 15–&lt; 60</td>
<td>20–130</td>
<td>20–60</td>
</tr>
<tr>
<td>Optimum</td>
<td>30</td>
<td>80</td>
<td>25–30</td>
</tr>
<tr>
<td>G+C content of DNA (mol%)</td>
<td>33·1</td>
<td>26·9</td>
<td>23·2–25·2</td>
</tr>
<tr>
<td>Stickland reaction</td>
<td>Positive</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Reduction of S(_0^2)</td>
<td>–</td>
<td>ND</td>
<td>+</td>
</tr>
<tr>
<td>Reduction of thiosulfate</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Substrates used:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellobiose</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Fructose</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Galactose</td>
<td>+</td>
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<td>W</td>
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<td>Glycerol</td>
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<td>Dulcitol</td>
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<td>+</td>
<td>ND</td>
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<tr>
<td>Sorbitol</td>
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<td>+</td>
<td>–</td>
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<tr>
<td>Products of glucose fermentation:</td>
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</tr>
<tr>
<td>Ethanol</td>
<td>–</td>
<td>+</td>
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<tr>
<td>Propionate</td>
<td>+</td>
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</tr>
<tr>
<td>Lactate</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

Data were taken from this study (strain DVird3\(^T\), Fendrich et al. (1990) (\textit{Clostridium halophilum}) and Alain et al. (2002b) (\textit{Caminicella sporogenes}). –, negative; +, positive; ND, not determined; w, weak growth.
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