Petrotoga halophila sp. nov., a thermophilic, moderately halophilic, fermentative bacterium isolated from an offshore oil well in Congo

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A novel thermophilic, moderately halophilic, rod-shaped bacterium, strain MET-B\textsuperscript{T}, with a sheath-like outer structure (toga) was isolated from an offshore oil-producing well in Congo, West Africa. Strain MET-B\textsuperscript{T} was a Gram-negative bacterium with the ability to reduce elemental sulfur, but not sulfate, thiosulfate or sulfite into sulfide. The optimum growth conditions were 60 °C, pH 6.7–7.2 and 4–6 % NaCl. The DNA G+C content was 34.6 mol%. Strain MET-B\textsuperscript{T} was phylogenetically related to members of the genus Petrotoga; Petrotoga miotherma, Petrotoga olearia and Petrotoga mexicana were the closest relatives, with type strains exhibiting more than 99 % identity in an analysis of small-subunit rRNA gene sequences. The values for DNA–DNA relatedness between the type strains of these three species and strain MET-B\textsuperscript{T} were less than 42 %. As MET-B\textsuperscript{T} was found to be genetically and physiologically different from other species of the genus Petrotoga, this strain is proposed as representing a novel species, for which the name Petrotoga halophila sp. nov. is proposed. The type strain is MET-B\textsuperscript{T} (= DSM 16923\textsuperscript{T} = CCUG 50214\textsuperscript{T}).

Members of the order Thermotogales (e.g. Thermotoga, Geotoga and Petrotoga species), considered as exclusively thermophilic micro-organisms, are known as common inhabitants of petroleum reservoirs (Magot et al., 2000; Ollivier & Cayol, 2005). Their occurrence within the oilfield environment was established in the 1990s by Stetter et al. (1993) and Davey et al. (1993). However, in contrast to Thermotoga species, which have been isolated from various hot ecosystems throughout the world (e.g. thermal springs, hydrothermal vents), Geotoga and Petrotoga species have been found only in oil reservoirs (Ollivier & Cayol, 2005). In this respect, it has been suggested that members of the latter two genera might represent typical indigenous micro-organisms in this particular subterrestrial ecosystem (Ollivier & Cayol, 2005). Two Geotoga species and five Petrotoga species have been characterized so far. The genus Petrotoga comprises Petrotoga miotherma, P. mobilis, P. olearia and P. sibirica, which originated from brines obtained from petroleum reservoirs located in Oklahoma and Texas (Davey et al., 1993), a North Sea oil-production well (Lien et al., 1998) and a continental petroleum reservoir in Western Siberia (P. olearia and P. sibirica; L’Haridon et al., 2002), respectively. More recently, Petrotoga mexicana was recovered from an oil reservoir in the Gulf of Mexico (Miranda-Tello et al., 2004).

Here we report on the isolation and characterization of a novel bacterial strain (MET-B\textsuperscript{T}), isolated from an offshore oil well in Africa. Although this strain is phylogenetically closely related to the five species of the genus Petrotoga, it exhibits significant phenotypic and genetic differences that are consistent with its placement within a novel species.

Strain MET-B\textsuperscript{T} was isolated from an oil/water mixture collected from well TBM111 of the Chibouella oilfield (Congo). The oil produced was slightly biodegraded, with
selective and complete removal of the n-alkanes (Connan et al., 1996), and the in-situ temperature and NaCl concentration were 45 °C and 98 g l⁻¹. The samples were collected in sterile glass bottles and kept at 4 °C until use. P. miottherma ATCC 51224T was obtained from the American Type Culture Collection (Manassas, VA, USA). P. olearia DSM 13574T was obtained from the Institut Universitaire Européen de la Mer (Plouzané, France) and P. mexicana DSM 14811T was obtained from our culture collection in Marseille.

The enrichment culture was performed in 60 ml serum bottles inoculated with 2 ml sample. The medium contained the following (1 l⁻¹ distilled water): 0.2 g NH₄Cl, 0.3 g K₂HPO₄, 0.3 g KH₂PO₄, 0.1 g KCl, 0.1 g CaCl₂, 0.5 g MgCl₂·6H₂O, 90 g NaCl 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-solution (Balch et al., 1979), using medium solidified with 0.8 % Phytagel (Difco). The strain was isolated by repeated use of the Hungate roll-tube technique (Hungate, 1969), using medium solidified with 0.8 % Phytagel (Difco). The process of serial dilution in roll tubes was repeated at least twice in order to purify the cultures.

Growth experiments were performed in duplicate, using Hungate tubes containing basal medium. The basal medium was the same as the enrichment medium but without potassium nitrate or sodium acetate and with 0.2 % yeast extract.

The pH, temperature and NaCl concentration ranges for growth were determined using basal medium supplemented with 20 mM glucose. The pH of the medium was adjusted to 7 with 10 M KOH. The medium was boiled under a stream of O₂-free N₂ gas; 20 ml was dispensed into serum bottles under a stream of N₂/CO₂ (80 : 20, v/v) gas, and the sealed vessels were autoclaved for 45 min at 110 °C. Prior to inoculation, yeast extract, potassium nitrate and sodium acetate were injected from sterile stock solutions to final concentrations of 1 g l⁻¹, 10 mM and 20 mM, respectively. The bottles were incubated at 50 °C in a controlled-temperature incubator and three enrichment series were performed in the same medium before isolation. The strain was isolated by repeated use of the Hungate roll-tube technique (Hungate, 1969), using medium solidified with 0.8 % Phytagel (Difco). The process of serial dilution in roll tubes was repeated at least twice in order to purify the cultures.

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Genomic DNA of strain MET-BT was extracted with the Wizard Genomic DNA purification kit (Promega), and the small-subunit rRNA gene (positions 8–1492, Escherichia coli numbering) was PCR-amplified (30 cycles) with the eubacteria-specific primers 8F (5'–AGAGTTTGATCCTGGCTCAG–3') and 1492R (5'–GTCGTAACGAACTACGACT–3'), as described previously (Thabet et al., 2004). The PCR product was purified (Nucleo Spin Extract kit; Macherey Nagel) and cloned using the pGEM-T-easy cloning kit (Promega). A plasmid containing an insert of the correct length was purified with the Wizard Plus SV Minipreps DNA purification system (Promega). The inserts of three plasmids obtained from independent cloning experiments were sequenced by Genome Express (Grenoble, France) using HPLC as described by Mesbah et al. (1989).
DNA–DNA hybridizations were performed at the DSMZ, as described previously (Miranda-Tello et al., 2004).

Enrichment cultures were incubated at 50 °C for 2 weeks. Microscopic examination of the enrichment culture revealed the presence of rods with an outer sheath-like structure (toga). Circular, white colonies that were 2.0 mm in diameter appeared after 1 week incubation in roll tubes at 50 °C. Several non-motile strains similar in morphology, unable to reduce thiosulfate and producing the same end-products of glucose metabolism were isolated, but only strain MET-BT was characterized further. The cells were 0.5–0.7 μm in width and 2–45 μm in length and occurred singly or in sheaths containing up to five cells (data not shown). The cells were not motile and no spore formation was detected. Electron microscopy of thin sections of strain MET-BT revealed a typical toga cell-wall ultrastructure with a spongy periplasmic layer (data not shown). The cells stained Gram-negative. Strain MET-BT was thermophilic and grew at temperatures ranging from 45 to 65 °C, with an optimum at 60 °C. The isolate was moderately halophilic and grew in the presence of NaCl concentrations ranging from 5 to 90 g l⁻¹, with an optimum between 40 and 60 g l⁻¹. The optimum pH range for growth was 6.7–7.2 and growth occurred between pH 5.6 and 7.8. Strain MET-BT fermented D-arabinose, cellobiose, fructose, galactose, and growth occurred between pH 5.6 and 7.8. Strain MET-BT differed from P. olearia by not using peptone and by fermenting galactose (Table 1). Phenotypic differences were also observed between P. mexicana and strain MET-BT, as the latter did not use thiosulfate as a terminal electron acceptor (Table 1). Finally, the optimum NaCl contents ranging from 34 to 36.1 mol%. Culture enrichments that we performed to recover heterotrophic nitrate-reducing micro-organisms from an offshore oil well in Congo (West Africa) led to the isolation of strain MET-BT, which was able to use glucose as an energy source, but unable to use nitrate as a terminal electron acceptor. This strain showed phenotypic characteristics and genomic properties (e.g. a DNA G+C content of 34.6 mol%) that were consistent with its placement within the genus Petrotoga rather than the genus Geotoga. Moreover, small-subunit rRNA gene analysis based on 1248 unambiguous nucleotides confirmed that strain MET-BT should be considered as a member of the genus Petrotoga, its closest phylogenetic relatives being the type strains of P. miotherma (Davey et al., 1993), P. olearia (L’Haridon et al., 2002), P. mexicana (Miranda-Tello et al., 2004) and P. sibirica (L’Haridon et al., 2002), which showed sequence similarities of 99.7, 98.8, 99.0 and 98.5 %, respectively (Fig. 1). P. sibirica clearly differs from our isolate and the Petrotoga species cited above as it does not grow at 60 °C and does not use the same range of substrates (Table 1). Moreover, despite the existence of close phylogenetic relationships between strain MET-BT and P. miotherma, P. olearia and P. mexicana, a DNA–DNA hybridization analysis revealed relatedness values of only 41.9, 25.9 and 31.1 %, respectively, with respect to the type strains of these species. Therefore, according to the criteria of Wayne et al. (1987), strain MET-BT is not related to these bacteria at the species level and should be considered as a novel species within the genus Petrotoga. In contrast to P. miotherma, strain MET-BT fermented xylan and did not produce ethanol from sugar metabolism, but produced lactate (Table 1). Strain MET-BT differed from P. olearia by the absence of motility, by not using peptone and by fermenting galactose (Table 1). Phenotypic differences were also observed between P. mexicana and strain MET-BT, as the latter did not use thiosulfate as a terminal electron acceptor (Table 1). Finally, the optimum NaCl

Members of the order Thermotogales, comprising anaerobic, rod-shaped micro-organisms whose cells are surrounded by sheath-like structures (like strain MET-BT), are recognized as common inhabitants of deep, hot oil reservoirs located in marine or continental ecosystems (Magot et al., 2000; Ollivier & Cayol, 2005). Of these, it is noteworthy that species belonging to the genera Geotoga or Petrotoga have been isolated only from petroleum environments, indicating that they might be indigenous to moderately deep and hot oil reservoirs (Ollivier & Cayol, 2005). The genus Petrotoga comprises five species, each of which is considered as being moderately thermophilic to thermophilic (i.e. with an optimum temperature for growth between 55 and 60 °C) heterotrophs growing in habitats covering a broad range of salt concentrations (0.5–20 %, depending on the species). In addition, they have DNA G+C contents ranging from 34 to 36.1 mol%. Culture enrichments that we performed to recover heterotrophic nitrate-reducing micro-organisms from an offshore oil well in Congo (West Africa) led to the isolation of strain MET-BT, which was able to use glucose as an energy source, but unable to use nitrate as a terminal electron acceptor. This strain showed phenotypic characteristics and genomic properties (e.g. a DNA G+C content of 34.6 mol%) that were consistent with its placement within the genus Petrotoga rather than the genus Geotoga. Moreover, small-subunit rRNA gene analysis based on 1248 unambiguous nucleotides confirmed that strain MET-BT should be considered as a member of the genus Petrotoga, its closest phylogenetic relatives being the type strains of P. miotherma (Davey et al., 1993), P. olearia (L’Haridon et al., 2002), P. mexicana (Miranda-Tello et al., 2004) and P. sibirica (L’Haridon et al., 2002), which showed sequence similarities of 99.7, 98.8, 99.0 and 98.5 %, respectively (Fig. 1). P. sibirica clearly differs from our isolate and the Petrotoga species cited above as it does not grow at 60 °C and does not use the same range of substrates (Table 1). Moreover, despite the existence of close phylogenetic relationships between strain MET-BT and P. miotherma, P. olearia and P. mexicana, a DNA–DNA hybridization analysis revealed relatedness values of only 41.9, 25.9 and 31.1 %, respectively, with respect to the type strains of these species. Therefore, according to the criteria of Wayne et al. (1987), strain MET-BT is not related to these bacteria at the species level and should be considered as a novel species within the genus Petrotoga. In contrast to P. miotherma, strain MET-BT fermented xylan and did not produce ethanol from sugar metabolism, but produced lactate (Table 1). Strain MET-BT differed from P. olearia by the absence of motility, by not using peptone and by fermenting galactose (Table 1). Phenotypic differences were also observed between P. mexicana and strain MET-BT, as the latter did not use thiosulfate as a terminal electron acceptor (Table 1). Finally, the optimum NaCl

Fig. 1. Phylogenetic dendrogram, based on small-subunit rRNA gene sequence data, indicating the position of strain MET-BT with respect to all known species of the family Thermotogaceae. Bootstrap values above 50% are shown. Bar, 2 nucleotide substitutions per 100 nucleotides.
concentration for growth strain of MET-B\textsuperscript{T} was higher (4–6\%) than that of any Petrotoga species, so the novel isolate should be considered as a moderate halophile (Table 1). Therefore, on the basis of the phenotypic and phylogenetic data in this study, strain MET-B\textsuperscript{T} represents a novel species within the genus Petrotoga, for which the name Petrotoga halophila sp. nov. is proposed.

**Description of Petrotoga halophila sp. nov.**

*Petrotoga halophila* (ha.lo'phi.la. Gr. n. halos salt; Gr. adj. philos loving; N.L. fem. adj. halophila salt-loving).

Cells are rods, 0.5–0.7 × 2–45 μm in size, with an outer sheath-like structure (toga), occurring singly or in sheaths. Electron microscopy of sections of cells exhibits a Gram-negative-type cell wall. Flagella are not observed. No spore formation is detected. Grows at temperatures in the range 45–65 °C, with an optimum at 60 °C. Grows in the presence of NaCl at concentrations ranging from 5 to 90 g l\(^{-1}\), with an optimum at 40–60 g l\(^{-1}\). The optimum pH for growth is 6.7–7.2, but growth occurs between pH 5.6 and 7.8. Ferments D-arabinose, cellobiose, fructose, galactose, glucose, lactose, maltose, rhamnose, ribose, starch, sucrose, xylose, xylan and pyruvate. Under anaerobic conditions, glucose is fermented into acetate, lactate, L-alanine, H\(_2\) and CO\(_2\). No L-alanine is produced in the presence of elemental sulfur as the terminal electron acceptor. Acetate, fumarate, succinate, mannose, raffinose, methanol, Casamino acids, peptone and H\(_2\) are not used. Elemental sulfur is used as a terminal electron acceptor, but sulfate, sulfite, thiosulfate, fumarate, nitrate and nitrite are not. Grows with chloramphenicol, kanamycin and vancomycin (each at 10 μg ml\(^{-1}\)) and with 50 μg rifampicin ml\(^{-1}\). The DNA G + C content is 34.6 mol\% (HPLC).

The type strain, MET-B\textsuperscript{T} (= DSM 16923\textsuperscript{T} = CCUG 50214\textsuperscript{T}), was isolated from an oil well in Congo, West Africa.

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**References**


E. Miranda-Tello and others