Shewanella loihica sp. nov., isolated from iron-rich microbial mats in the Pacific Ocean

Haichun Gao,1,2,3 Anna Obraztova,4 Nathan Stewart,2 Radu Popa,5 James K. Fredrickson,6 James M. Tiedje,2 Kenneth H. Nealson4 and Jizhong Zhou1,3

Correspondence
Jizhong Zhou
jzhou@ou.edu

1Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA
2Center for Microbial Ecology, Michigan State University, East Lansing, MI, USA
3Stephenson Research and Technology Center, Institute for Environmental Genomics, University of Oklahoma, 101 David L. Boren Boulevard, Norman, OK 73019, USA
4Department of Biological Sciences, University of Southern California, Los Angeles, CA, USA
5Department of Biology, Portland State University, Portland, OR, USA
6Pacific Northwest National Laboratory, Richland, WA, USA

A novel marine bacterial strain, PV-4T, isolated from a microbial mat located at a hydrothermal vent of Loihi Seamount in the Pacific Ocean, has been characterized. This micro-organism is orangey in colour, Gram-negative, polarly flagellated, facultatively anaerobic and psychrotolerant (temperature range, 0–42°C). No growth was observed with nitrate, nitrite, DMSO or thiosulfate as the electron acceptor and lactate as the electron donor. The major fatty acid detected in strain PV-4T was iso-C15 : 0. Strain PV-4T had ubiquinones consisting mainly of Q-7 and Q-8, and possessed menaquinone MK-7. The DNA G+C content of the strain was 53±8 mol% and the genome size was about 4·5 Mbp. Phylogenetic analyses based on 16S rRNA gene sequences placed PV-4T within the genus Shewanella. PV-4T exhibited 16S rRNA gene sequence similarity levels of 99·6 and 97·5%, respectively, with respect to the type strains of Shewanella aquimarina and Shewanella marisflavi. DNA from strain PV-4T showed low mean levels of relatedness to the DNAs of S. aquimarina (50·5%) and S. marisflavi (8·5%). On the basis of phylogenetic and phenotypic characteristics, the bacterium was classified in the genus Shewanella within a distinct novel species, for which the name Shewanella loihica sp. nov. is proposed. The type strain is PV-4T (= ATCC BAA-1088T = DSM 17748T).

The genus Shewanella consists of rod-shaped, Gram-negative, facultatively anaerobic, readily cultivated gammaproteobacteria (Gauthier et al., 1995; MacDonell & Colwell, 1985; Venkateswaran et al., 1999). While many Shewanella strains remain uncharacterized, there are 32 recognized Shewanella species: the latter were isolated from a variety of sources, primarily aquatic environments and sediments (Bowman et al., 1997; Bozal et al., 2002; Brettar et al., 2002; Coyne et al., 1989; Ivanova et al., 2001, 2003a, b, 2004a, b, c; Leonardo et al., 1999; Makemson et al., 1997; Nogi et al., 1998; Nozue et al., 1992; Satomi et al., 2003, 2006; Skerratt et al., 2002; Toffin et al., 2004; Venkateswaran et al., 1998, 1999; Xu et al., 2005; Yoon et al., 2004a, b; Zhao et al., 2005, 2006; Ziemke et al., 1998). The bacteria of this genus have attracted great attention because of their diverse respiratory capacities, illustrated by their ability to utilize a wide range of terminal electron acceptors, including oxygen, nitrate, metals and sulfur compounds (Kostka et al., 1996; Myers & Nealson, 1988; Venkateswaran et al., 1999; http://www.shewanella.org). Some Shewanella strains are also able to degrade pollutants such as chlorinated solvents (Petrovskis et al., 1994), petroleum (Semple & Westlake, 1987) and RDX (1,3,5-trinitroperhydro-1,3,5-triazine) (Zhao et al., 2004), some can produce polyunsaturated fatty acids (Bowman et al., 1997; Russell & Nichols, 1999; Satomi et al., 2003) and some are able to grow under extreme conditions (Bozal et al., 2002; Kato et al., 1998; Nogi et al., 1998; Stapleton et al., 2005).

In a previous study, several Shewanella strains were isolated from marine-sediment samples at a variety of locations in the Pacific Ocean (Stapleton et al., 2005). Among these...
strains was *Shewanella* sp. PV-4T, which was isolated from iron-rich microbial mats at the active, deep-sea, hydrothermal Naha Vent (1325 m below sea level) located on the South Rift of Loihi Seamount, Hawaii (http://www.soest.hawaii.edu/GG/HCV/loihivents.html). Although the draft genome sequence of strain PV-4T was released recently (by the Joint Genome Institute; see http://www.jgi.doe.gov) and its morphology, metal-reduction capacity and biomineralization ability have been explored, its taxonomic status has remained undefined (Roh et al., 2006). The objective of the present study was to establish the taxonomic position of strain PV-4T, by using a combination of polyphasic taxonomic data.

Standard protocols, including those for determining the Gram reaction, catalase and oxidase activities and spore formation (Smibert & Krieg, 1994), were employed to establish the physiological and biochemical properties of strain PV-4T. Enzymic hydrolysis of various substrates, including casein, starch, gelatin, Tweens 20, 40 and 80 and DNA, and a determination of the production of H2S from thiosulfate were conducted, using marine broth 2216, as described elsewhere (Smibert & Krieg, 1994; Bowman et al., 1997). Other phenotypic and enzymic characterizations of strain PV-4T were conducted using API 20E, API ID 32A and API ZYM test kits (bioMérieux) and Biolog PM plates (Biolog), according to the instructions of the manufacturers. The pH and temperature ranges for growth were determined on marine 2216 medium (Difco). The requirement for Na+ ions was studied using a medium described elsewhere (Ivanova et al., 2003b). Salt-tolerance tests were performed on marine 2216 medium with NaCl concentrations of 0.5–8.0% (w/v). The reduction of electron acceptors was assessed using M1 defined medium supplemented with lactate (10 mM) as the electron donor and one of the electron acceptors as described previously (Roh et al., 2006). The reduction of electron acceptors with N-acetylglucosamine (10 mM) as the electron donor was examined in this study by using the same procedure. The electron acceptor tests included MnO2 (5 mM), ferric citrate (20 mM), ferric EDTA (10 mM), akaganeite (Fe3O8; 70 mM), cobalt [Co(III)] EDTA (1.5 mM), potassium chromate [Cr(VI)]; 0.5 mM), uranyl [U(VI)] carbonate (5 mM), hydrous ferric oxides (40 mM), DMSO (10 mM), sodium nitrate (3 mM), sodium nitrite (0.5 mM), sulfur (40 mM), sodium thiosulfate (5 mM), sodium sulfate (5 mM), sodium sulfite (5 mM) and trimethylamine-N-oxide (10 mM).

The morphological, physiological and biochemical characteristics of strain PV-4T are given in Table 1. Consistent with species of the genus *Shewanella*, strain PV-4T is a rod-shaped bacterium with a single polar flagellum (Roh et al., 2006). Biomass of strain PV-4T exhibited an orangey colour under aerobic conditions. In general, the physiological and biochemical characteristics of strain PV-4T are typical of species of the genus *Shewanella* (Venkateswaran et al., 1999). However, strain PV-4T exhibits some unique features. Strain PV-4T was found to be psychrotolerant and able to grow over unusually wide ranges of temperature (0–42°C), pH (4.5–10) and salt (0.5–5%). The optimal temperature, pH and salt concentration for growth were 18°C, pH 6–8 and 2%, respectively. In contrast to most *Shewanella* species, strain PV-4T was able to utilize acetate, propionate or Tween 40. Unlike some *Shewanella* species, strain PV-4T does not show any growth with nitrate, nitrite, thiosulfate, sulfate, sulfite, sulfitic or DMSO as the electron acceptor and lactate as the electron donor.

For quantitative analysis of cellular fatty acid compositions, cell mass of strains PV-4T and *Shewanella aquimarina* JCM 12193T was obtained from Luria–Bertani agar plates after cultivation for 2 days at room temperature and fatty acid profiles were determined using the Sherlock System (MIDI) at the University of Florida, Gainesville, FL, USA (http://plantpath.ifas.ufl.edu/fame/). Isoprenoid quinones were extracted and analysed as described by

---

**Table 1. Characteristics that differentiate strain PV-4T from phylogenetically related species**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA G+C content (mol%)</td>
<td>54</td>
<td>45</td>
<td>54</td>
<td>46</td>
<td>51</td>
<td>43</td>
</tr>
<tr>
<td>Growth in/at:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4°C</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>42°C</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>0% NaCl</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>8% NaCl</td>
<td>–</td>
<td>V</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>pH 4:5</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>ND</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>pH 10</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>ND</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Reduction of nitrate to nitrite</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>H2S from thiosulfate</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>α-Glucosidase</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>ND</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>β-Glucosidase</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>ND</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Utilization of:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fumarate</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Galactose</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Glucose</td>
<td>+</td>
<td>+</td>
<td>ND</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Citrate</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Lactate</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Malate</td>
<td>+</td>
<td>ND</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Maltose</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>N-Acetylglucosamine</td>
<td>+</td>
<td>ND</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Succinate</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
</tbody>
</table>
Ivanova et al. (2003b). The cellular fatty acids observed in PV-4T were similar to those of S. aquimarina JCM 12193T, ranging from C_{12} to C_{18} and included saturated, monoenoic, straight-chain and iso-branched components (see Supplementary Table S1, available in IJSEM Online). Major fatty acids included C_{12:0}, C_{13:0}, 3-OH, C_{15:0}, C_{16:0}, C_{17:0}, C_{17:1}, C_{18:0}, C_{18:1} \alpha. Strain PV-4T contained ubiquinones, consisting mainly of Q-7 and Q-8, and menaquinone MK-7. However, methylenquinones were not detected.

The DNA G+C content of strain PV-4T is 53.8 mol% and the genome size is 4.5 Mbp (on the basis of the draft genome sequence). The almost-complete 16S rRNA gene sequence for strain PV-4T was also amplified and sequenced as described elsewhere (Roh et al., 2006). Other Shewanella 16S rRNA gene sequences were obtained from GenBank or the Ribosomal Database Project (http://rdp.cme.msu.edu/index.jsp). Sequence alignment and phylogenetic relationships were established with the neighbour-joining DNA distance program in the MEGA3 package (Kumar et al., 2004) (Fig. 1). The phylogenetic analysis clearly showed that strain PV-4T belonged to the genus Shewanella. The 16S rRNA gene sequence of strain PV-4T showed 99.6 and 97.5% similarity, respectively, to those of the type strains of its nearest phylogenetic relatives, S. aquimarina and Shewanella marisflavi. The levels of 16S rRNA gene sequence similarity between strain PV-4T and the type strains of other recognized Shewanella species were below 96.5%. As reported by Stackebrandt & Goebel (1994), species definition in general requires 16S rRNA sequence similarities greater than 97.5%. Thus, strain PV-4T could be a strain belonging to the species S. aquimarina or S. marisflavi.

To determine whether PV-4T is a strain within S. aquimarina or S. marisflavi, DNA–DNA hybridizations were performed between PV-4T and S. aquimarina JCM 12193T and between PV-4T and S. marisflavi JCM 12192T. Genomic DNA was extracted from these two strains for DNA–DNA hybridization, as described previously (Zhou et al., 1996). DNA hybridizations were carried out using the microplate procedure, as described elsewhere (Goris et al., 1998). Strain PV-4T displayed mean DNA–DNA relatedness values of 50.5 and 8.5% with respect to S. aquimarina JCM 12193T and S. marisflavi JCM 12192T, respectively. As these values are below the 70% similarity threshold specified by Wayne et al. (1987), strain PV-4T should be considered as representing a different species within the genus Shewanella.

In summary, on the basis of phenotypic, physiological, chemotaxonomic, phylogenetic and genetic data, we propose that strain PV-4T represents a novel species of

**Fig. 1.** Phylogenetic tree, based on 16S rRNA gene sequences, showing the taxonomic position of strain PV-4T within the genus Shewanella. The tree was created using the neighbour-joining method included in MEGA3. Numbers at nodes indicate bootstrap percentages. Bar, 5 nucleotide differences per 1000 positions.
**Description of Shewanella loihica sp. nov.**

Shewanella loihica (lo.i.hi’ca. N.L. fem. adj. loihica of Loihi Seamount, where the type strain was isolated).

Gram-negative, non-spore-forming, straight rod with a mean length of 1.8 μm and a mean width of 0.7 μm. Motile by means of a single polar flagellum. Facultative psychrotolerant anaerobe. Colonies are smooth, glistening, circular, flat to slightly raised, orange in colour and 2.0–4.0 mm in diameter after 2 days incubation in air at room temperature on Luria–Bertani agar plates. Grows at temperatures ranging from 0 to 42 °C, with 18 °C as the optimum. Does not grow at temperatures above 43 °C. pH range for growth is 4.5–10.0 (optimum, pH 6.0–8.0). Na⁺ is required for growth. Grows at 0.5–5% NaCl, with an optimum at 2% NaCl; does not grow in the presence of more than 6% NaCl. Grows under anaerobic conditions. With lactate as the substrate, fumarate, MnO₂, ferric citrate, akaganeite, sulfur, sulfate, sulfite and DMSO are not. Susceptible to chloramphenicol, erythromycin, gentamicin, kanamycin, rifampicin and tetracycline. Slightly susceptible to spectinomycin and tetracycline. Resistant to ampicillin.

Description of Shewanella loihica sp. nov.

The type strain, PV-4T (= ATCC BAA-1088 = DSM 17748T), was isolated from iron-rich microbial mats at the active, deep-sea, hydrothermal Naha Vent located on the South Rift of Loihi Seamount, Hawaii, in the Pacific Ocean.

**Acknowledgements**

We would like to thank Dr Joel A. Klappenbach for advice on DNA–DNA hybridization. This research was supported by the Department of Energy Office of Biological and Environmental Sciences under the ‘Genomics: GTL Program’ via the Shewanella Federation. Oak Ridge National Laboratory is managed by University of Tennessee-Battelle LLC for the Department of Energy under contract DE-AC05-00OR22725.

**References**


