Complete genome sequence of the facultatively anaerobic, appendaged bacterium *Muricauda ruestringensis* type strain (B1^T)

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Muricauda ruestringensis Bruns *et al.* 2001 is the type species of the genus *Muricauda*, which belongs to the family *Flavobacteriaceae* in the phylum *Bacteroidetes*. The species is of interest because of its isolated position in the genomically unexplored genus *Muricauda*, which is located in a part of the tree of life containing not many organisms with sequenced genomes. The genome, which consists of a circular chromosome of 3,842,422 bp length with a total of 3,478 protein-coding and 47 RNA genes, is a part of the ***G**enomic **E**ncyclopedia of **B**acteria and **A**rchaea* project.

Introduction

Strain B1^T (= DSM 13258 = LMG 19739 = KCTC 12928) is the type strain of the species *Muricauda ruestringensis*, which is the type species of the currently six species containing genus *Muricauda* [1,2]. The genus name was derived from the Latin words *muris*, of the mouse, and *cauda*, the tail; *Muricauda*, tail of the mouse, referring to the cellular appendages observed on some cells [1]. The species epithet is derived from the Neo-Latin word *ruestringensis*, pertaining to the former village of Rüstringen, which was destroyed by a tidal wave in 1362 [1]. Stain B1^T was isolated from a seawater sediment suspension from intertidal sediment at the German North Sea coast, which contained hexadecane as the sole carbon source during the initial cultivation. Later, the organism either turned out to be unable to degrade hexadecane or lost its ability to do so [1]. Other isolates belonging to the species are not known, nor was strain B1^T used for scientific work other than the description of the species *M. ruestringensis*. Here we present a summary classification and a set of features for *M. ruestringensis* strain B1^T, together with the description of the complete genomic sequencing and annotation.

Classification and features

A representative genomic 16S rRNA sequence of *M. ruestringensis* B1T was compared using NCBI BLAST [3,4] under default settings (e.g., considering only the high-scoring segment pairs (HSPs) from the best 250 hits) with the most recent release of the Greengenes database [5] and the relative frequencies of taxa and keywords (reduced to their stem [6]) were determined, weighted by BLAST scores. The most frequently occurring genera were *Muricauda* (24.7%), *Maribacter* (24.0%), *Cytophaga* (12.3%), *Zobellia* (9.6%) and *Flavobacterium* (7.1%) (118 hits in total). Regarding the two hits to sequences from members of the species, the average identity within HSPs was 99.7%, whereas the average coverage by HSPs was 93.8%. Regarding the six hits to sequences from other members of the genus, the average identity within HSPs was 97.9%, whereas the average coverage by HSPs was 97.9%. Among all other species, the one yielding the highest score was *Muricauda aquimarina* (EU440979), which corresponded to an identity of 98.7% and an HSP coverage of 98.4%. (Note that the Greengenes database uses the INSDC (= EMBL/NCBI/DDBJ) annotation, which is not an authoritative source for nomenclature or classification.) The highest-scoring environmental sequence was HQ326265 ('Microbial structure biofilm on SWRO membranes clone SBS-FW-047'), which showed an identity of 98.5% and an HSP coverage of 98.0%. The most frequently occurring keywords within the labels of all environmental samples which yielded hits were 'microbi' (4.7%), 'sediment' (4.1%), 'sea' (2.9%), 'marin' (2.4%) and 'biofilm' (2.4%), (132 hits in total). Environmental samples which yielded hits of a higher score than the highest scoring species were not found.

Figure 1 shows the phylogenetic neighborhood of *M. ruestringensis* in a 16S rRNA based tree. The sequences of the two identical 16S rRNA gene copies in the genome differ by one nucleotide from the previously published 16S rRNA sequence (AF218782).

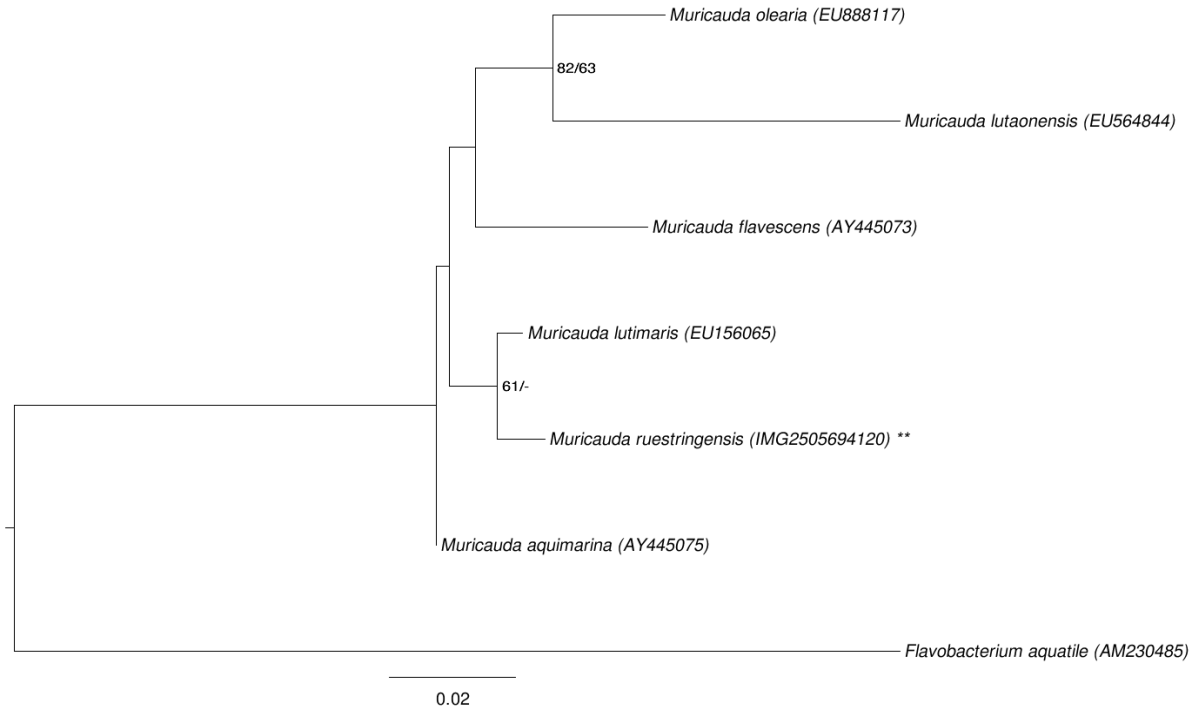

Figure 1. Phylogenetic tree highlighting the position of *M. ruestringensis* relative to the type strains of the other species within the genus *Muricauda*. The tree was inferred from 1,481 aligned characters [7,8] of the 16S rRNA gene sequence under the maximum likelihood (ML) criterion [9]. *Flavobacterium aquatile* was included in the dataset for use as outgroup taxa. The branches are scaled in terms of the expected number of substitutions per site. Numbers adjacent to the branches are support values from 850 ML bootstrap replicates [10] (left) and from 1,000 maximum-parsimony bootstrap replicates [11] (right) if larger than 60%. Lineages with type strain genome sequencing projects registered in GOLD [12] are labeled with one asterisk, those also listed as 'Complete and Published' with two asterisks.

Cells of strain B1^T are rod-shaped with rounded ends, 0.3 - 0.6 µm wide and 1.1 - 2.7 µm long (Figure 2 and Table 1) [1]. Cells of older cultures are characterized by mainly polar appendages with vesicle-like structures (blebs) at the end (Figure 2), which were discussed in detail by Bruns *et al*. in [1] and probably serve to contact cells to each other or for colonization of a substratum [1]. The non-motile cells (see missing genes in the motility category in COGs table) stain Gram-negative and grow as facultative anaerobes in seawater. The temperature range for growth is between 8°C and 40°C, with an optimum between 20 and 30°C [1]. The pH range for growth is 6.0-8.0, with an optimum at pH 6.5-7.5 [1]. Physiology and metabolism are discussed in detail in [1], with the surprising discovery that although strain B1^T was isolated from a continuous-flow culture containing hexadecane as a sole carbon source, the strain was unable to degrade hexadecane (even if it was offered as cosubstrate along with other carbon sources); nor could it use acetate or pyruvate as sole carbon sources, but required a wide spectrum of amino acids as carbon and energy sources in addition to some carbohydrates [1].

Chemotaxonomy

The spectrum of whole-cell fatty acids represents the only chemotaxonomical data published thus far for strain B1^T. The spectrum of fatty acids was dominated by branched-chain acids (72%): *iso*-$C_{17:0\ 3OH}$ (28.7%), *iso*-$C_{15:1}$ (16.3%), *iso*-$C_{15:0}$ (15.5%), *iso*-$C_{15:0\ 3OH}$ (4.9%), *iso*-$C_{16:0\ 3OH}$ (2.9%), *iso*-$C_{17:0\ 2OH}$ (2.8%), *iso* -$C_{15:0\ 2OH}$ (2.5%), $C_{16:1\ \omega7c}$ (2.5%), *anteiso*-$C_{15:0}$ (2.4%), other acids below 2% [1].

Genome sequencing and annotation

Genome project history

This organism was selected for sequencing on the basis of its phylogenetic position [29], and is part of the ***G**enomic **E**ncyclopedia of **B**acteria and **A**rchaea* project [30]. The genome project is deposited in the Genomes On Line Database [12] and the complete genome sequence is deposited in GenBank. Sequencing, finishing and annotation were performed by the DOE Joint Genome Institute (JGI). A summary of the project information is shown in Table 2.

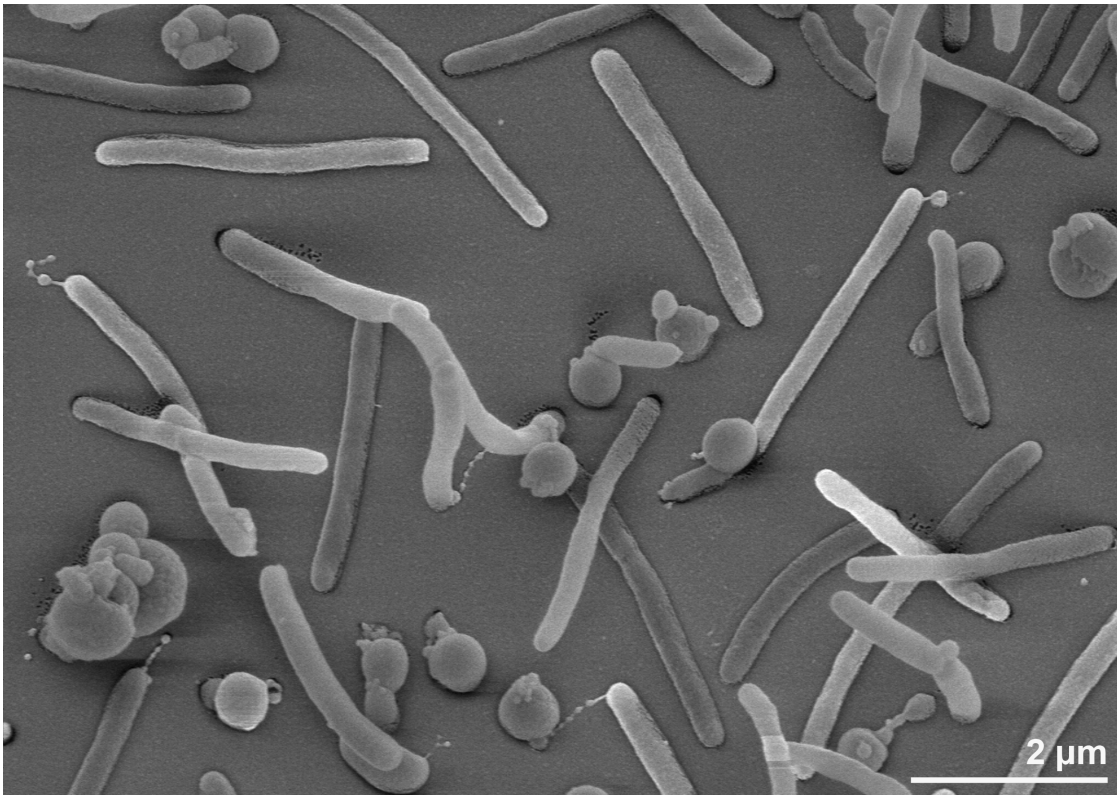

Figure 2. Scanning electron micrograph of *M. ruestringensis* B1^T

Table 1. Classification and general features of *M. ruestringensis* B1T according to the MIGS recommendations [13].

MIGS ID	Property	Term	Evidence code
	Current classification	Domain *Bacteria*	TAS [14]
		Phylum *Bacteroidetes*	TAS [15,16]
		Class *Flavobacteria*	TAS [17,18]
		Order *Flavobacteriales*	TAS [19,20]
		Family *Flavobacteriaceae*	TAS [21-24]
		Genus *Muricauda*	TAS [1,25,26]
		Species *Muricauda ruestringensis*	TAS [1]
		Type strain B1	TAS [1]
	Gram stain	negative	TAS [1]
	Cell shape	rod-shaped	TAS [1]
	Motility	non-motile	TAS [1]
	Sporulation	not reported	
	Temperature range	mesophile, 20°C–30°C	TAS [1]
	Optimum temperature	30°C	TAS [1]
	Salinity	slightly halophilic, optimum 3% NaCl (w/v)	TAS [1]
MIGS-22	Oxygen requirement	facultatively anaerobic	TAS [1]
	Carbon source	various sugars and amino acids	TAS [1]
	Energy metabolism	chemoheterotroph	TAS [1]
MIGS-6	Habitat	marine	TAS [1]
MIGS-15	Biotic relationship	free-living	TAS [1]
MIGS-14	Pathogenicity	none	NAS
	Biosafety level	1	TAS [27]
	Isolation	seawater sediment suspension	TAS [1]
MIGS-4	Geographic location	Jadebusen Bay, coast of North Sea, Germany	TAS [1]
MIGS-5	Sample collection time	1998 or earlier	NAS
MIGS-4.1	Latitude	53.45	NAS
MIGS-4.2	Longitude	8.20	NAS
MIGS-4.3	Depth	not reported	
MIGS-4.4	Altitude	about 0 m, sea level	NAS

Evidence codes - NAS: Non-traceable Author Statement (i.e., not directly observed for the living, isolated sample, but based on a generally accepted property for the species, or anecdotal evidence). These evidence codes are from the Gene Ontology project [28].

Growth conditions and DNA isolation

M. ruestringensis strain B1T, DSM 13258, was grown in DSMZ medium 917 (Modified Sea Water Agar) [31] at 30°C. DNA was isolated from 0.5-1 g of cell paste using Jetflex Genomic DNA Purification Kit (GENOMED 600100) following the manufacturer's instructions, with a modified procedure for cell lysis: incubation with 40 µl proteinase K for 40 minutes at 58°C. DNA is available through the DNA Bank Network [32].

Genome sequencing and assembly

The genome was sequenced using a combination of Illumina and 454 sequencing platforms. All general aspects of library construction and sequencing can be found at the JGI website [33].

Pyrosequencing reads were assembled using the Newbler assembler (Roche). The initial Newbler assembly consisting of 26 contigs in one scaffold was converted into a phrap [34] assembly by making fake reads from the consensus, to collect the read pairs in the 454 paired end library. Illumina GAii sequencing data (3,847 Mb) was assembled with Velvet [35] and the consensus sequences were shredded into 1.5 kb overlapped fake reads and assembled together with the 454 data. The 454 draft assembly was based on 268.3 Mb 454 draft data and all of the 454 paired end data. Newbler parameters are -consed -a 50 -l 350 -g -m -ml 20. The Phred/Phrap/Consed software package [34] was used for sequence assembly and quality assessment in the subsequent finishing process. After the shotgun stage, reads were assembled with parallel phrap (High Performance Software, LLC). Possible mis-assemblies were corrected with gapResolution [33], Dupfinisher [36], or sequencing cloned bridging PCR fragments with subcloning. Gaps between contigs were closed by editing in Consed, by PCR and by Bubble PCR primer walks (J.-F. Chang, unpublished). A total of 46 additional reactions were necessary to close gaps and to raise the quality of the finished sequence. Illumina reads were also used to correct potential base errors and increase consensus quality using a software Polisher developed at JGI [37]. The error rate of the completed genome sequence is less than 1 in 100,000. Together, the combination of the Illumina and 454 sequencing platforms provided 1,032.9 × coverage of the genome. The final assembly contained 422,407 pyrosequence and 49,819,141 Illumina reads.

Genome annotation

Genes were identified using Prodigal [38] as part of the Oak Ridge National Laboratory genome annotation pipeline, followed by a round of manual curation using the JGI GenePRIMP pipeline [39]. The predicted CDSs were translated and used to search the National Center for Biotechnology Information (NCBI) nonredundant database, UniProt, TIGR-Fam, Pfam, PRIAM, KEGG, COG, and InterPro databases. Additional gene prediction analysis and functional annotation was performed within the Integrated Microbial Genomes – Expert Review (IMG-ER) platform [40].

Genome properties

The genome consists of a 3,842,422 bp long circular chromosome with a G+C content of 41.4% (Table 3 and Figure 3). Of the 3,525 genes predicted, 3,478 were protein-coding genes, and 47 RNAs; 46 pseudogenes were also identified. The majority of the protein-coding genes (66.6%) were assigned a putative function while the remaining ones were annotated as hypothetical proteins. The distribution of genes into COGs functional categories is presented in Table 4.

Table 2. Genome sequencing project information

MIGS ID	Property	Term
MIGS-31	Finishing quality	Finished
MIGS-28	Libraries used	Four genomic libraries: one 454 pyrosequence standard library, two 454 PE libraries (4 kb and 8 kb insert size), one Illumina library
MIGS-29	Sequencing platforms	Illumina GAii, 454 GS FLX Titanium
MIGS-31.2	Sequencing coverage	996.4 × Illumina; 36.4 × pyrosequence
MIGS-30	Assemblers	Newbler version 2.3, Velvet version 0.7.63, phrap version SPS - 4.24
MIGS-32	Gene calling method	Prodigal 1.4, GenePRIMP
	INSDC ID	CP002999
	Genbank Date of Release	August 19, 2011
	GOLD ID	Gc01927
	NCBI project ID	52467
	Database: IMG-GEBA	2505679007
MIGS-13	Source material identifier	DSM 13258
	Project relevance	Tree of Life, GEBA

Table 3. Genome Statistics

Attribute	Value	% of Total
Genome size (bp)	3,842,422	100.00%
DNA coding region (bp)	3,479,569	90.56%
DNA G+C content (bp)	1,589,148	41.36%
Number of replicons	1	
Extrachromosomal elements	0	
Total genes	3,525	100.00%
RNA genes	47	1.33%
rRNA operons	2	
tRNA genes	38	1.08%
Protein-coding genes	3,478	98.67%
Pseudo genes	46	1.30%
Genes with function prediction	2,349	66.64%
Genes in paralog clusters	1,644	46.64%
Genes assigned to COGs	2,433	69.02%
Genes assigned Pfam domains	2,500	70.92%
Genes with signal peptides	970	27.52%
Genes with transmembrane helices	809	22.95%
CRISPR repeats	0	

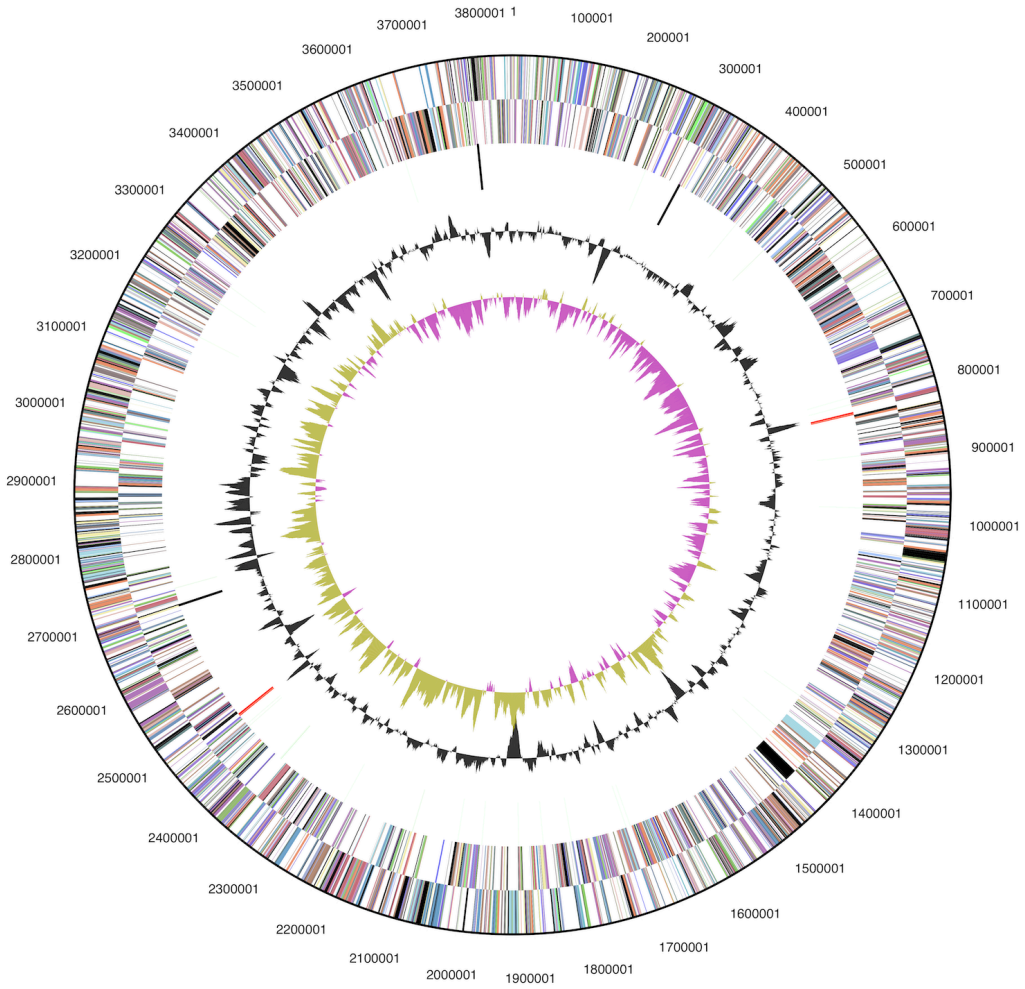

Figure 3. Graphical map of the chromosome. From outside to the center: Genes on forward strand (color by COG categories), Genes on reverse strand (color by COG categories), RNA genes (tRNAs green, rRNAs red, other RNAs black), GC content, GC skew.

Table 4. Number of genes associated with the general COG functional categories

Code	value	%age	Description
J	151	5.8	Translation, ribosomal structure and biogenesis
A	0	0.0	RNA processing and modification
K	206	7.9	Transcription
L	130	5.0	Replication, recombination and repair
B	2	0.1	Chromatin structure and dynamics
D	23	0.9	Cell cycle control, cell division, chromosome partitioning
Y	0	0.0	Nuclear structure
V	77	2.9	Defense mechanisms
T	145	5.5	Signal transduction mechanisms
M	186	7.1	Cell wall/membrane/envelope biogenesis
N	7	0.3	Cell motility
Z	1	0.0	Cytoskeleton
W	0	0.0	Extracellular structures
U	50	1.9	Intracellular trafficking, secretion, and vesicular transport
O	106	4.0	Posttranslational modification, protein turnover, chaperones
C	129	4.9	Energy production and conversion
G	136	5.2	Carbohydrate transport and metabolism
E	220	8.4	Amino acid transport and metabolism
F	65	2.5	Nucleotide transport and metabolism
H	138	5.3	Coenzyme transport and metabolism
I	86	3.3	Lipid transport and metabolism
P	141	5.4	Inorganic ion transport and metabolism
Q	49	1.9	Secondary metabolites biosynthesis, transport and catabolism
R	339	12.9	General function prediction only
S	236	9.0	Function unknown
-	1,092	31.0	Not in COGs

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