**Geobacter pickeringii** sp. nov., **Geobacter argillaceus** sp. nov. and **Pelosinus fermentans** gen. nov., sp. nov., isolated from subsurface kaolin lenses

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**INTRODUCTION**

Kaolin is a rock consisting predominantly of the clay mineral kaolinite, which is important for the production of paper as well as porcelain and ceramics. It is mined worldwide from subsurface kaolin lenses and has varying degrees of purity and whiteness. Kaolinite is a product of the weathering of aluminium silicate minerals, with feldspar being the most common source mineral. When conditions are favourable for weathering, white kaolin without discolouring impurities, such as iron oxides (goethite, hematite), sulfide (pyrite) and organic matter, is formed (Hurst & Pickering, 1997; Elzea Kogel et al., 2002). Depending on their origin, kaolins and kaolin-containing source rocks are either mildly acidic (pH 5–5.5) (Elzea Kogel et al., 2002) or slightly alkaline (pH 7–8.5) (Solodkii, 1995).

The goal of this project was to isolate representative Fe(III)-reducing bacteria from kaolin clays that may influence iron mineralogy in kaolin. Two novel dissimilatory Fe(III)-reducing bacteria, strains G12T and G13T, were isolated from sedimentary kaolin strata in Georgia (USA). Cells of strains G12T and G13T were motile, non-spore-forming regular rods, 1–2 μm long and 0.6 μm in diameter. Cells had one lateral flagellum. Phylogenetic analyses using the 16S rRNA gene sequence of the novel strains demonstrated their affiliation to the genus **Geobacter**. Strain G12T was most closely related to **Geobacter pelophilus** (94.7 %) and **Geobacter chapellei** (94.1 %). Strain G13T was most closely related to **Geobacter grbiciae** (95.3 %) and **Geobacter metallireducens** (95.1 %). Based on phylogenetic analyses and phenotypic differences between the novel isolates and other closely related species of the genus **Geobacter**, the isolates are proposed as representing two novel species, **Geobacter argillaceus** sp. nov. (type strain G12T = ATCC BAA-1139T = JCM 12999T) and **Geobacter pickeringii** sp. nov. (type strain G13T = ATCC BAA-1140T = DSM 17153T = JCM 13000T). Another isolate, strain R7T, was derived from a primary kaolin deposit in Russia. The cells of strain R7T were motile, spore-forming, slightly curved rods, 0.6 x 2.0–6.0 μm in size and with up to six peritrichous flagella. Strain R7T was capable of reducing Fe(III) only in the presence of a fermentable substrate. 16S rRNA gene sequence analysis demonstrated that this isolate is unique, showing less than 92 % similarity to bacteria of the **Sporomusa–Pectinatus–Selenomonas** phyletic group, including 'Anaerospora hongkongensis' (90.2 %), **Acetotetra longum** (90.6 %), **Dendrosporobacter quercicolus** (90.9 %) and **Anaerosinus glycerini** (91.5 %).

On the basis of phylogenetic analysis and physiological tests, strain R7T is proposed to represent a novel genus and species, **Pelosinus fermentans** gen. nov., sp. nov. (type strain R7T = DSM 17108T = ATCC BAA-1133T), in the **Sporomusa–Pectinatus–Selenomonas** group.
Subsurface kaolin lenses are not optimal environments for microbial growth due to the fine mineral particle size of clay and consequently the low hydraulic conductivity. However, cultivation-dependent most probable number analysis (Shelobolina et al., 1999, 2005) and cultivation-independent lipid biomarker analysis (Osipov & Turova, 1997) have shown the presence of a variety of physiological groups of micro-organisms in kaolin samples of differing ages and origins collected from distant geographical locations in Russia, Ukraine and the USA. Stimulation of indigenous iron-reducing bacteria in kaolin results in a decrease of the Fe(III):[Fe(II) + Fe(III)] ratio (Shelobolina et al., 1999, 2005), iron solubilization (Turova et al., 1996; Lee et al., 1999; Shelobolina et al., 1999) and in a dramatic increase in the efficacy of iron extraction by magnetic separation (Turova et al., 1996; Vodyanitskii et al., 1997; Shelobolina et al., 1999). The ability of indigenous bacteria to influence iron mineralogy in kaolin suggests that bacteria have played a significant role in the natural removal of iron impurities from kaolin at the subsurface (Hurst & Pickering, 1997; Elzea Kogel et al., 2002; Shelobolina et al., 2005) and can be used for the development of microbially mediated industrial-scale iron removal from tinted kaolin (Avakyan et al., 1997; Lee et al., 1999). The goal of this project was to isolate representative Fe(III)-reducing bacteria from kaolin clays that might be involved in these processes. Three novel anaerobic Gram-negative micro-organisms were isolated from subsurface kaolin lenses in Russia and the USA. Two strains conserved energy from the oxidation of the organic matter with the reduction of Fe(III), whereas the third organism was capable of reducing Fe(III) only in the presence of a fermentable substrate.

**METHODS**

**Study sites and sample collection.** Strains G12T and G13T were isolated from subsurface kaolin lenses in Georgia (USA). Strain G12T was isolated from tan kaolin of the Late Paleocene age from the Thiele Kaolin Co. Avant mine, 1 km west of GA highway 272, GA. Strain G13T was isolated from kaolin from the Huber Formation of the Eocene age taken from the Thiele General Refractories clay mine, 3.2 km south of Tabernacle Church, GA. Both samples were collected in November 1999. Large pieces of kaolin were taken from freshly exposed surfaces in active mines using a mine excavator and/or a geological pickaxe. Samples were then wrapped with plastic and sent by an overnight delivery service to the laboratory. After arrival at the laboratory, all samples were placed into an N2-filled glove bag. Large pieces of kaolin samples were broken with sterile knives. The middle portion of the samples was extracted, homogenized and dispensed into serum bottles (160 ml) for immediate experimentation or into large (2000 ml) sterilized Pyrex bottles with thick rubber stoppers for storage and/or later use.

Strain R7T was isolated from primary kaolin of the Zhuravlinii Log diuvial deposit (located near the town of Plast, Chelabinsk region, Russia). Kaolin was collected in August 1995 using a mine excavator. The sample was placed in a large paper bag and shipped by regular mail to the State University of Management, Russia, to test its suitability for ceramics production. Immediately after arrival at the State University of Management, an aliquot of this kaolin was taken and placed into a large (1000 ml) sterilized bottle with a thick rubber stopper. The bottle headspace was gassed with N2. Microbial enrichments were established at the Institute of Microbiology of the Russian Academy of Sciences as part of a study into the role of micro-organisms within kaolins in the processes of iron solubilization and transformation (Shelobolina et al., 1999).

**Media and cultivation.** Strict anaerobic techniques (Miller & Wolin, 1974; Balch et al., 1979) were used throughout. An anaerobic basal bicarbonate-buffered freshwater (FW) medium (Lovley & Phillips, 1988) was dispensed into 27 ml anaerobic pressure tubes (Bellco Glass) or 160 ml serum bottles under N2/CO2 (80:20). The tubes or bottles were capped with butyl rubber stoppers and sterilized by autoclaving. The reducing agents were FeCl2 (1.3 mM) for Fe(III)-containing media and cysteine (0.5 mM) for all other media and these were added after the medium was autoclaved.

Enrichment cultures with Georgia kaolin (USA) were initiated in 160 ml serum bottles containing 90 ml freshwater medium and 10 g clay from the site. Poorly crystalline ferric oxide (PCFO) (100 mM l−1) was prepared as described previously (Lovley & Phillips, 1986a) and used as the terminal electron acceptor for enrichment and isolation of the strains. Enrichments were established with hydrogen, acetate (10 mM), lactate (10 mM) or intrinsic organic matter (no electron donor added) as the electron donors. Strain G12T was recovered from an enrichment culture established with intrinsic organic matter as the electron donor. The sample of tan kaolin from the Thiele Kaolin Co. Avant mine had 5.3% (w/w) of organic carbon. Acetate (10 mM) was the electron donor for the isolation of strain G12T. Strain G13T was isolated from an enrichment culture established with lactate (10 mM) as the electron donor. Isolates were recovered with a roll-tube method (Hungate, 1969). BBL agar (Becton Dickinson; 1.5%) was used as the solidifying agent. An inoculum (0.7 ml) from the 10-fold serial dilutions of the enrichment culture in a liquid FW medium was added to 27 ml pressure tubes containing 7 ml melted medium. The contents were mixed gently and the pressure tubes were rolled with a tube spinner (Bellco Glass). The roll-tubes were incubated vertically at 30 °C. Individual colonies were transferred to the pressure tubes with 2 ml liquid FW medium containing PCFO as the electron acceptor and either acetate (for strain G12T) or lactate (for strain G13T) as the electron donors.

The enrichment culture with Russian kaolin was initiated in 1995 and supported for 4 years in 27 ml pressure tubes containing 9 ml FW medium supplemented with 20 mM lactate and 100 mMl l−1 PCFO. In 1999, the original enrichment culture was transferred to FW medium containing hydrogen as the electron donor, acetate as the carbon source and 100 mMl l−1 PCFO as the electron acceptor. Strain R7T was isolated from the resulting enrichment culture, which was transferred onto anaerobic agar plates solidified with 1.2% agar (BBL agar; Becton Dickinson; 1.5%) and used as the terminal electron acceptor for enrichment and isolation of the strains. Enrichments were established with hydrogen, lactate (10 mM) or intrinsic organic matter (no electron donor added) as the electron donors. Strain R7T was recovered from an enrichment culture established with intrinsic organic matter as the electron donor. Agar plates were incubated vertically at 30 °C. Individual colonies were transferred to the pressure tubes with 2 ml liquid FW medium containing PCFO as the electron acceptor and either acetate (for strain G12T) or lactate (for strain G13T) as the electron donors.

**Screening of potential electron donors and acceptors.** The criterion used to determine whether isolates could utilize a particular electron donor or acceptor was the ability of the isolates to grow in presence of a potential donor or acceptor for 3–5 successive 10% transfers.

For strains G12T and G13T, the electron donor used to evaluate potential electron acceptors was acetate. Hydrogen was used for strain
Adding elemental sulfur (1 g l$^{-1}$) to a bright orange. Reduction of elemental sulfur was determined by monitoring as a colour change in the medium from an opaque pink to a bright orange. Reduction of elemental sulfur was monitored as the accumulation of Fe(II) or Mn(II). AQDS reduction was monitored as a colour change in the medium from an opaque pink to a bright orange. Reduction of elemental sulfur was determined by adding elemental sulfur (1 g l$^{-1}$) to the medium and monitoring sulfide production by the methylene blue method (Cline, 1969). Growth on the other electron acceptors was monitored by measuring turbidity at 600 nm. Controls contained no electron acceptor.

The ability of washed cell suspensions to reduce U(VI) was determined as previously described (Shelobolina et al., 2004) using uranyl acetate (1 mM) as the electron acceptor, acetate (5 mM) as the electron donor and the following reaction buffer (1 mM): 2.5 g NaHCO$_3$, 0.25 g NH$_4$Cl, 0.006 g NaH$_2$PO$_4$, 0.25 g KH$_2$PO$_4$, 0.1 g KOH. Cells were added to the reaction buffer to give a final protein concentration of 0.01 mg ml$^{-1}$.

Experiments to screen potential electron donors were performed in freshwater medium bubbled with N$_2$/CO$_2$ (80 : 20) and supplemented with either 100 mmol l$^{-1}$ PCFO (for strains G12$^T$ and G13$^T$) or 10 mmol Fe(III) NTa (for strain R7$^T$) as the electron acceptor. In order to decrease the amount of carry-over substrate, electron donor (acetate)-limited culture was used for the first transfer of strains G12$^T$ and G13$^T$. Alternative electron donors were added to the medium from sterile anoxic stock solutions to give a final concentration of 10–20 mM, except for amino acids that were tested at a final concentration of 0.1 g l$^{-1}$. Controls included no donor and donor alone (for potentially fermentable substrates).

**Analytical techniques.** Chelated and poorly crystalline forms of iron were quantified by the ferrozine assay (Lovley & Phillips, 1986b; Phillips & Lovley, 1987). Structural Fe(II) and Fe(III) in the clay were determined by hydrofluoric acid extraction followed by the 1,10-phenanthroline assay as described by Stucki (Stucki, 1981) and modified by Komadel and Stucki (Komadel & Stucki, 1988). Mn(II) concentrations were monitored as described previously (Kashefi & Lovley, 2000). Cells were counted with acridine orange staining and epifluorescence microscopy as described previously (Hobble et al., 1977).

**16S rRNA gene sequencing and phylogenetic analysis.** DNA was extracted from strains G12$^T$, G13$^T$ and R7$^T$ using the FastDNA SPIN kit (Bio101). The 16S rRNA gene was amplified using the bacterial forward primer 8F (AGAGTTTGATCMTGCGCTGAG) and the universal reverse primer 1525R (AAGAGGTTGATCMTGGCTCAG). These primers and the conserved internal primers 338F (AC-TCTACGGGAGGCAGC), 519F (CAGGACGCGCCGGGTATLFWC), 519R (GAWATTACGCGGCCGCGTCG), 907R (CGTCAATTCMT-TTRAGTTC) and 1392R (ACGGCGGTGTGTRCR) were used to obtain the nearly complete sequence. PCR mixtures contained: a 1 x concentration of Q and Taq polymerase buffers (Qiagen), 0.5 µg bovine serum albumin, 200 µM deoxyribonucleoside triphosphates (Sigma-Aldrich), 25 pmol forward and reverse primers (Sigma) and 1.25 U Taq polymerase (Qiagen). PCR tubes containing all the reaction components except the template and Taq polymerase were UV irradiated for 7 min to ensure sterility. Reactions were performed in a Peltier thermal cycler (PTC 200) beginning with a 5 min denaturation at 95 °C and then 25–30 cycles of 94 °C (30 s), 45 °C (1 min), 72 °C (1 min) and a final 10 min elongation at 72 °C. The 16S rRNA gene fragments from strains G12$^T$ and G13$^T$ and R7$^T$ were compared with the GenBank nucleotide and protein databases using the BLASTN and BLASTX algorithms (Altschul et al., 1990). Representative sequences from the Sporomusa–Pectinatus–Selenomonas group, members of the genus Geobacter and other genera were obtained from GenBank for phylogenetic analysis. Nucleotide sequences were manually aligned in the Genetic Computer Group (GCG) sequence editor (Wisconsin Package version 10). Aligned sequences were imported into PAUP 4.0b4a (Swofford, 1998) where phylogenetic trees were inferred. Identical branching orders were observed with maximum-parsimony and distance-based algorithms when 16S rRNA gene sequences were compared. Bootstrap values were calculated by distance analysis.

**Determination of the G+C content of DNA.** The Deutsche Sammlung von Mikroorganismen und Zellkulturen identification performed the DNA G+C content analysis for strain R7$^T$ (Cashion et al., 1977). The DNA G+C content of strains G12$^T$ and G13$^T$ was determined using a fluorometric technique employing real-time PCR (Gonzalez & Saiz-Jimenez, 2002, 2004). Genomic DNA standards from Clostridium acetobutylicum (ATCC 824D; 30 mol% G+C), Escherichia coli K-12 (ATCC 700926; 50 mol% G+C), Pseudomonas aeruginosa PAO1 (ATCC 47085D; 66 mol% G+C) and Halobacterium sp. (ATCC 700922D; 67 mol% G+C) were obtained from the ATCC. Thermal denaturation was performed with approximately 2.5 µg DNA from each novel isolate. Thermal conditions consisted of a ramp from 55 °C to 90 °C at 0.5 °C min$^{-1}$ on a Bio-Rad iCycler. Fluorescent melt curves for each sample and standard DNA were generated in triplicate. The DNA G+C content for strains G12$^T$ and G13$^T$ was calculated using linear regression analyses of melting temperatures ($T_m$) against the G+C content of the standard DNA.

**RESULTS AND DISCUSSION**

**Characteristics of strains G12$^T$ and G13$^T$.** Cells of strains G12$^T$ and G13$^T$ were Gram-negative, motile, regular rods, 1–2 µm long and 0.6 µm in diameter. On anaerobic solidified FW medium, colonies were 1–2 mm in diameter. Colonies were pink on fumarate (20 mM, strain G13$^T$) due to the high c-type cytochrome content of cells of the genus Geobacter (Lovley et al., 2004) and black on PCFO (100 mM, strains G12$^T$ and G13$^T$) due to formation of dark coloured Fe(II)-bearing minerals such as magnetite (Lovley et al., 1987). When grown with Fe(III) as the electron acceptor, cells had one lateral flagellum (Fig. 1a, b).

Cells of strain G13$^T$ exhibited multiple short and elongated tubular projections (blebs) on the cell surface (Fig. 1b). Although blebbing of outer membrane (OM) followed by formation of membrane vesicles has been described for a number of other Gram-negative bacteria (Beveridge, 1999; Kuehn & Kesty, 2005), this is the first Geobacter species for which formation of large quantities of blebs has been demonstrated. There are several hypotheses for the formation of blebs. Blebbing of the OM could be an overproduction of OM, compared with peptidoglycan (Wensink & Witholt, 1981) or the result of cell wall turnover during growth (Zhou et al., 1998). Blebbing of the
OM increases the surface area of the cells, which might improve nutrient uptake. Formation of blebs in an Fe(III)-reducing bacterium, Acidophilium cryptum JF-5, has been hypothesized to enhance cellular contact with non-soluble Fe(III) hydroxides that are utilized as electron acceptors (Küsel et al., 1999). In addition, when OM vesicles form as the result of OM blebbing, they entrap some of the underlying periplasm which enables the bacteria to secrete proteins, lipids and DNA into the extracellular medium (Forsberg et al., 1981; Dorward et al., 1989; Dorward & Garon, 1990; Kadurugamuwa & Beveridge, 1996; Kadurugamuwa et al., 1998; Li et al., 1998; Ciofu et al., 2000; Kobayashi et al., 2000; Yaron et al., 2000). Vesicles can also mediate the coaggregation of bacteria, enabling biofilm formation and colonization (Grenier & Mayrand, 1987; Whitchurch et al., 2002). Therefore, the formation of blebs may give strain G13T a growth advantage over other micro-organisms.

With acetate (20 mM) as the electron donor and ferric citrate (50 mM) as the electron acceptor, growth of strains G12T and G13T was most rapid at 30 °C and there was no growth at temperatures below 10 °C. The upper growth temperature was 36 °C. Optimal pH for growth was 6.2–6.8 for strain G12T and pH 6.6–7.2 for strain G13T. No growth was observed at pH values lower than 5.8 for either isolate. The upper pH value for growth was 7.4 for strain G12T and 8.0 for strain G13T.

With acetate (20 mM) serving as the electron donor, both strains were capable of reducing the following electron acceptors: 60–100 mmol PCFO l−1, ferric citrate (50 mM), Fe(III) NTA (10 mM), Fe(III) pyrophosphate (10 mM), 30 mmol MnOOH l−1 and 1 g elemental sulfur l−1 (Table 1). In addition, strain G13T reduced a humic acid analogue, AQDS, fumarate (20 mM) and malate (20 mM). Strain G12T also reduced nitrate (5 mM). Both strains were able to reduce U(VI) (1 mM) in cell suspension. The following electron acceptors were tested but not utilized by either strain: oxygen (5 % of the headspace of the culture), sulfate (10 mM), sulfite (10 mM) and nitrite (5 mM). With PCFO as the electron acceptor, the isolates were capable of oxidizing the following electron donors (at concentrations 10–20 mM): ethanol, butanol, glycerol, acetate, lactate, butyrate, pyruvate and valerate. Strain G13 was also able to use methanol and succinate.

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Fig. 1. Morphology of negatively stained cells of strains G12T (a) and G13T (b). Both strains were grown on acetate as the electron donor and PCFO as the electron acceptor. Cells were harvested in the middle exponential phase. Cells of strain G13T exhibit short and elongated tubular projections (blebs) on the cell surface (b, shown with arrows). Bars, 0.5 μm.

Table 1. Characteristics that differentiate strains G12T and G13T and related species of the genus Geobacter

The G+C content of the DNA was 58.0 mol% for strain G12<sup>T</sup> and 61.4 mol% for strain G13<sup>T</sup>.

**Characteristics of strain R7<sup>T</sup>**

Cells of strain R7<sup>T</sup> were motile, slightly curved rods, 0.6 × 2.0–6.0 μm (Fig. 2a). Spores were formed in the late exponential phase on all growth substrates. Spores were oval and always in a terminal position (Fig. 2b). The sporangia were distinctly swollen. The presence of up to six flagella was observed by electron microscopy. Flagella were peritrichous and up to 14 μm long and 15 nm wide. Ultrathin sections showed a Gram-negative type of cell wall, with the peptidoglycan layer and outer membrane clearly visible (Fig. 2b).

Optimal growth conditions for this strain were determined using FW medium supplemented with 20 mM glucose. Optimal growth was observed at 22–30 °C and no growth was observed at an initial temperature lower than 4 °C or higher than 36 °C. The pH range for growth was between 5.5 and 8, with an optimum at pH 7.

With hydrogen as the electron donor and acetate as the carbon source, strain R7<sup>T</sup> was not capable of utilizing oxygen, AQDS, nitrate, sulfate, sulfite, thiosulfate, Fe(III) NTA, PCFO or elemental sulfur as the electron acceptor. Resting cells of strain R7<sup>T</sup> did not reduce U(VI) when hydrogen was provided as the electron donor.

Although strain R7<sup>T</sup> was enriched as a Fe(III) reducer, once isolated, this organism was capable of reducing Fe(III) only in the presence of a fermentable substrate. Strain R7<sup>T</sup> could reduce ferric citrate (FC, Fig. 3a) or Fe(III) pyrophosphate (data not shown), but not Fe(III) NTA (Fig. 3a). The observed growth and reduction of Fe(III) when FC and Fe(III) pyrophosphate were provided as the electron acceptors can be explained by the presence of fermentable citrate and organic impurities in these substrates. Acetate was the major product of citrate fermentation by strain R7<sup>T</sup>, with an acetate/citrate ratio of 1.9:1. This ratio decreased slightly in the presence of FC alone (1.7:1) or FC and hydrogen (1.4:1) (Fig. 3b). The presence of hydrogen did not increase the Fe(III) reduction rate (Fig. 3a) or cell yield.
(Fig. 3c), suggesting that strain R7T could not use hydrogen as an electron donor. As follows from Fig. 3c, strain R7T was not able to grow chemoheterotrophically on H2/CO2. Strain R7T reduced 0.3 mM Fe(III) per 1 mM citrate fermented. Together, these data suggest that strain R7T, as with other fermentative bacteria (Dobbin et al., 1999; Park et al., 2001; Kim et al., 2005; Bhushan et al., 2006), utilizes Fe(III) as an electron sink. Strain R7T was also capable of reducing small quantities (1–1.5 mM) AQDS in the presence of fermentable substrates, such as citrate or lactate (data not shown). The use of AQDS as a sink has been demonstrated for several fermentative bacteria, including species of the genera Clostridium (Bhushan et al., 2006) and Cellulomonas (Borch et al., 2005).

Strain R7T fermented the following substrates: lactate, butyrate, pyruvate, malate, succinate, citrate, fumarate, fructose, glucose, mannitol, peptone, Casamino acids and yeast extract. The following substrates were tested but not utilized: glycerol, salicylic acid, ascorbate, 2,3-butanediol, maltose, gallic acid, pyrogallol, asparagines, histidine, glycine, leucine, lysine, serine, tyrosine, methionine, phenylalanine, proline, tryptophan, valine, glutamic acid and aspartic acid.

Phylogenetic analyses

BLAST and similarity analyses of 16S rRNA gene sequences indicated that strain G12T was most similar to Geobacter pelophilus (sequence similarity 94.7%) and Geobacter chapellei (94.1%). Strain G13T was most similar to G. grbicicae (95.3%) and Geobacter metallireducens (95.1%) in the class Deltaproteobacteria. Strain R7T was most similar to the following micro-organisms of the Sporomusa–Pectinatus–Selenomonas phyletic group: ‘Anaerospora hongkongensis’ (gene sequence similarity 90.2%), Acetomona longum (90.6%), Denitrosporobacter quercicola (90.9%) and Anaerosinus glycini (91.5%).

Phylogenetic analysis of these and other related sequences was performed using 1200 (Fig. 4a) and 1300 (Fig. 4b) bases for comparison. Placement of strains G12T, G13T and R7T was consistent when using distance and maximum-parsimony analyses (Fig. 4a, b). The results indicated that strain G12T was phylogenetically most closely related to G. chapellei and strain G13T was most closely related to Geobacter hydrogenophilus, G. metallireducens and G.

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Fig. 4. Phylogenetic analysis of strains G12T, G13T and R7T. (a) Phylogenetic tree comparing 16S rRNA gene sequences from the kaolin isolates. Thermotoga maritima and ‘Aquifex aeolicus’ served as outgroups for the construction of the 16S rRNA gene tree. 1200 positions were considered. (b) Phylogenetic position of strain R7T within the Sporomusa–Pectinatus–Selenomonas phyletic group. Thermotoga maritima served as an outgroup for the construction of this tree. 1300 positions were considered. Numbers next to branches indicate bootstrap values obtained from 100 replicates by maximum-parsimony/maximum based analysis. Asterisk indicates that distance analysis does not show separate branching for uncultured Clostidium clone FW29. Bars, 50 nucleotide changes.
grbicicis (Fig. 4a). Based on the phenotypic differences between isolates G12T and G13T and closely related species of the genus Geobacter (Table 1), it is suggested that the isolates represent two novel species, Geobacter argillaceus sp. nov. (strain G12T) and Geobacter pickeringii sp. nov. (strain G13T).

Isolate R7T grouped with members of the Sporomusa–Pectinatus–Selenomonas phyletic group of the phylum Firmicutes (Stro¨mpl et al., 1999), which is also referred to as clostridial cluster IX (Collins et al., 1994) or the ‘Sporomusa branch’ (Biebl et al., 2000) (Fig. 4a, b). This phyletic group contains a heterogeneous assemblage of organisms with Gram-negative cell walls, some of which are spore-forming. Strain R7T was phylogenetically most closely related to Acetonema longum (Fig. 4b). Because of the low degree of similarity of the 16S rRNA gene sequence of strain R7T with the closest members of the Sporomusa–Pectinatus–Selenomonas group, as well as significant phenotypic differences (Table 2), we propose to classify this strain as a representative of a new genus and species, Pelosinus fermentans.

Table 2. Characteristics that differentiate strain R7T and related members of the Sporomusa–Pectinatus–Selenomonas group

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA G + C content (mol%)</td>
<td>41.0</td>
<td>51.5</td>
<td>52.0–54.0</td>
<td>35.0</td>
<td>46.8</td>
</tr>
<tr>
<td>Cell shape</td>
<td>Slightly curved rods</td>
<td>Straight rods</td>
<td>Straight rods</td>
<td>Curved rods</td>
<td>Straight or slightly curved rods</td>
</tr>
<tr>
<td>Cell size (µm)</td>
<td>0.6 × 2–6</td>
<td>0.6 × 6–60</td>
<td>0.5 × 3</td>
<td>0.5 × 2–10</td>
<td>0.4–0.6 × 3.15–14.30</td>
</tr>
<tr>
<td>Temperature range (°C)</td>
<td>4–36</td>
<td>19–40</td>
<td>20–45</td>
<td>10–42</td>
<td>37</td>
</tr>
<tr>
<td>Temperature optimum (°C)</td>
<td>22–30</td>
<td>30–33</td>
<td>25–30</td>
<td>37</td>
<td>ND</td>
</tr>
<tr>
<td>pH range</td>
<td>5.5–8</td>
<td>6.4–8.6</td>
<td>ND</td>
<td>5–8.5</td>
<td>ND</td>
</tr>
<tr>
<td>pH optimum</td>
<td>7</td>
<td>7.8</td>
<td>ND</td>
<td>6.5–7.5</td>
<td>ND</td>
</tr>
<tr>
<td>Flagella</td>
<td>Up to 6 peririchious</td>
<td>1–3 peririchious</td>
<td>1–3 peririchious</td>
<td>Not found</td>
<td>Polar flagellae or a tuft of flagellae inserted on one side</td>
</tr>
<tr>
<td>Spore formation</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Growth on:</td>
<td>Fructose</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Fumarate</td>
<td>+</td>
<td>+</td>
<td>ND</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Glucose</td>
<td>+</td>
<td>+</td>
<td>ND</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Glycerol</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>H₂+CO₂</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Lactate</td>
<td>+</td>
<td>−</td>
<td>ND</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Malate</td>
<td>+</td>
<td>−</td>
<td>ND</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Mannitol</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
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<td></td>
<td>Pyruvate</td>
<td>+</td>
<td>+</td>
<td>ND</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Succinate</td>
<td>+</td>
<td>−</td>
<td>ND</td>
<td>−</td>
</tr>
</tbody>
</table>

Potential role of the novel isolates in iron cycling in kaolin strata

Of the three organisms described in this paper, two of the isolates are dissimilatory Fe(III)-reducing bacteria and belong to the genus Geobacter. Like other representatives of this genus (Lovley & Phillips, 1988; Caccavo et al., 1994; Coates et al., 1996; Straub et al., 1998; Sung et al., 2006), these isolates are capable of obtaining energy for growth by coupling the reduction of Fe(III) to complete the oxidation of acetate with the ratio of Fe(II) produced per acetate consumed close to 8:1. In contrast, strain R7T represents a fermentative organism that is capable of reducing Fe(III) only in the presence of a fermentable substrate. Strain R7T produced only 0.3 mM Fe(II) per 1 mM citrate consumed (Fig. 3). However, despite their lower potential for Fe(III) reduction, fermentative bacteria can be important to the iron geochemistry of kaolin due to the high organic matter content in kaolin (0.1–5.3 %, w/w). The organic matter of kaolins contains various potential electron donors and fermentable substrates for bacterial metabolism such as formate, acetate, lactate, propionate, butyrate, pyruvate,
oxalate and citrate (Shelobolina et al., 1999, 2005) as well as humic and fulvic acids (Elzea Kogel et al., 2002). At the same time, kaolins are characterized by low amounts of ‘bioavailable’ Fe(III) (0.5 M HCl extractable hydroxylamine reducible; 0.0–0.9 mmol kg⁻¹) compared with total Fe(III) (hydrofluoric acid-extractable, 7.7–48.6 mmol kg⁻¹) (Shelobolina et al., 2005). Electron shuttling via humic acids can explain high levels of microbial Fe(III) reduction in kaolins in model experiments despite their low ‘bioavailable’ Fe(III) content (Shelobolina et al., 2005). The important role of fermentative bacteria in humic acid-mediated Fe(III) reduction has been demonstrated for freshwater lake sediments (Kappl er et al., 2004). Together, these data suggest that both dissimilatory Fe(III)-reducing and fermentative bacteria could be important contributors to microbial Fe(III) reduction in kaolin and can be used as model organisms to study biotransformations of iron minerals in kaolin.

**Description of Geobacter argillaceus sp. nov.**


Cells are Gram-negative, motile, regular rods, 1–2 μm long and 0.6 μm in diameter. Cells have one lateral flagellum. Optimal growth occurs at pH 6.2 to 6.8 and no growth occurs at initial pH values lower than 5.8 or higher than 7.4. Growth is most rapid at 30 °C; no growth occurs at temperatures below 10 °C or above 36 °C. Uses PCFO, ferric citrate, Fe(III) NCA, Fe(III) pyrophosphate, MnOOH, elemental sulfur and nitrate as electron acceptors. Reduces U(VI) in cell suspension. Oxidizes the following electron donors: methanol, ethanol, butanol, glycerol, acetate, lactate, butyrate, pyruvate, succinate and valerate. The G + C content of the DNA of the type strain is 61.4 mol%.

The type strain, G12T (= ATCC BAA-1139T = DSM 17153T = JCM 13000T), was isolated from sedimentary kaolin strata in Georgia, USA.

**Description of Pelosinus gen. nov.**

*Pelosinus* (Pe.lo.si.nus. Gr. masc. n. pelos mud or clay; L. masc. n. *sinus* bend; N.L. masc. n. *Pelosinus* a curved organism from clay).

Cells are Gram-negative, motile, slightly curved rods. Spore-forming. Sporangia are distinctly swollen. Obligately anaerobic. Mesophilic. Does not produce acetate from H₂ + CO₂. Fermentative. Uses a variety of fermentative substrates, but does not ferment glycerol. The type species is *Pelosinus fermentans*.

**Description of Pelosinus fermentans sp. nov.**


Displays the following features in addition to those given in the genus description. Cells are 2–6 μm long and 0.6 μm in diameter. Cells have up to 6 peritrichous flagella. Oval endospores are formed terminally. Optimal growth occurs at pH 7.0; no growth occurs at initial pH values lower than 5.5 or higher than 8.0. Growth is most rapid at 22–30 °C; no growth occurs at temperatures below 4 °C or above 36 °C. Does not respire anaerobically with Fe(III), AQDS, nitrate, sulfate, sulfite, thiosulfate or elemental sulfur, but is capable of using Fe(III) and AQDS as an electron sink in the presence of fermentable substrate. Does not reduce U(VI) in cell suspension. Ferments the following substrates: lactate, butyrate, pyruvate, malate, succinate, citrate, fumarate, fructose, glucose, mannitol, peptone, Casamino acids and yeast extract. The G + C content of DNA of the type strain is 41.0 mol%.

The type strain, R7T (= DSM 17108T = ATCC BAA-1133T), was isolated from subsurface primary kaolin deposits in Russia.

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