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Frederic Jorand, Asfaw Zegeye, Jaafar Ghanbaja, Mustapha Abdelmoula

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# **The formation of green rust induced by tropical river biofilm components**

Running title: **Green rust from ferruginous biofilms**

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Frédéric Jorand, Asfaw Zegeye, Jaafar Ghanbaja, Mustapha Abdelmoula

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## Abstract

15 In the Sinnamary Estuary (French Guiana), a dense red biofilm grows on flooded  
surfaces. In order to characterize the iron oxides in this biofilm and to establish the  
nature of secondary minerals formed after anaerobic incubation, we conducted solid  
analysis and performed batch incubations. Elemental analysis indicated a major  
amount of iron as inorganic compartment along with organic matter. Solid analysis  
20 showed the presence of two ferric oxides ferrihydrite and lepidocrocite. Bacteria were  
abundant and represented more than  $10^{11}$  cells  $g^{-1}$  of dry weight among which iron  
reducers were revealed. Optical and electronic microscopy analysis revealed that  
the bacteria were in close vicinity of the iron oxides. After anaerobic incubations with  
exogenous electron donors, the biofilm's ferric material was reduced into green rust,  
25 a  $Fe^{II}$ - $Fe^{III}$  layered double hydroxide. This green rust remained stable for several  
years. From this study and previous reports, we suggest that ferruginous biofilms  
should be considered as a favorable location for GR biomineralization when redox  
conditions and electron donors availability are gathered.

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30 Keywords: green rust; biofilm; iron oxide; lepidocrocite; ferrihydrite; biomineralization;  
solid analysis; secondary iron minerals

## 1. INTRODUCTION

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The green rust (GR) compounds are mixed Fe<sup>II</sup>-Fe<sup>III</sup> layered double hydroxide unstable under oxic conditions, and identified in several sub-oxic environments like corroded surface of Fe-based materials (Refait *et al.*, 2006), hydromorphic soils (Trolard *et al.*, 1997) or ground water (Christiansen *et al.*, 2009). The GR structure is related to that of the mineral fougérite (IMA 2003-057) (Génin *et al.*, 2005; Trolard *et al.*, 2007). The GRs are considered to be key components in biogeochemical cycle of iron (Herbillon, 2006) or in the applied research for polluted soil and water remediation processes due to their high reactivity towards oxidized organic (nitroaromatics, chloride derived,...) or inorganic compounds (Hg<sup>II</sup>, Se<sup>VI</sup>, Cr<sup>VI</sup>,...) (Myneni *et al.*, 1997; Erbs *et al.*, 1999; Loyaux-Lawniczak *et al.*, 2000; Refait *et al.*, 2000; O'Loughlin *et al.*, 2003). However, the mechanisms implied in their formation and whether or not bacteria are a major actor for their precipitation in natural environments, remain under investigation (Zegeye *et al.*, 2005 ; Zegeye *et al.*, 2007a ; Ahmed *et al.*, 2010 ; Salas *et al.*, 2010 ; Zegeye *et al.*, 2010).

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The dissimilatory iron-reducing bacteria (DIRB) are well recognized to be involved in the formation of secondary iron-II minerals. By coupling the reduction of Fe<sup>III</sup> to the oxidation of hydrogen or organic matter they gain energy for growth and the resulting Fe<sup>II</sup> mainly precipitates in several mineral phases such as magnetite (Fe<sub>3</sub>O<sub>4</sub>), siderite (FeCO<sub>3</sub>), chukanovite (Fe<sub>2</sub>OH<sub>2</sub>(CO<sub>3</sub>)), vivianite (Fe<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>•8H<sub>2</sub>O), the hydroxycarbonate green rust 1 (Fe<sup>II</sup><sub>4</sub>Fe<sup>III</sup><sub>2</sub>(OH)<sub>12</sub>CO<sub>3</sub>•~3H<sub>2</sub>O) and the hydroxysulfate green rust 2 (Fe<sup>II</sup><sub>4</sub>Fe<sup>III</sup><sub>2</sub>(OH)<sub>12</sub>SO<sub>4</sub>•~8H<sub>2</sub>O) (Lovley *et al.*, 1987; Jorand *et al.*, 2001; Glasauer *et al.*, 2002; Ona-Nguema *et al.*, 2002; Kukkadapu *et al.*, 2005; Zegeye *et al.*, 2005). The nature of the secondary iron mineral is partly controlled by the

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presence of its chemical constituents. For instance, phosphate or sulfate are needed  
55 to form vivianite or  $\text{GR}_2(\text{SO}_4^{2-})$ , respectively. But lower phosphate, concentration (i.e.  
undersaturated for vivianite precipitation) plays additional role, as organic polymers,  
bacterial cells or silicate, which is to promote the formation of GR over the magnetite  
without being constituent of this mineral. Thus, the supplementation of the incubation  
medium by microbial or synthetic polymers (polyacrylate) or autoclaved cells (Zegeye  
60 *et al.*, 2007a; Jorand *et al.*, 2008; O'Loughlin *et al.*, 2010; Zegeye *et al.*, 2010),  
phosphate (Kukkadapu *et al.*, 2004), quartz particles ( $\text{SiO}_2$ ), silicic acid ( $\text{H}_4\text{SiO}_4$ ) or a  
panel of oxyanions (O'Loughlin *et al.*, 2010; Sergent *et al.*, 2010) significantly  
promote the formation of GR1 over magnetite from lepidocrocite or ferrihydrite  
bioreduction.

65 The mechanisms involved in such secondary iron biomineralization remains under  
investigation. Recently, the organization of mixed aggregates constituted by iron  
oxide and bacterial cells was proposed to influence the GR vs magnetite  
mineralization routes (Zegeye *et al.*, 2010). It was suspected that an aggregate  
constituted by densely packed particles promotes areas at a micro-scale level. These  
70 micro-area would exhibit high concentrations of both bicarbonate and  $\text{Fe}^{\text{II}}$ , resulted  
from the bacterial metabolism, which would explain the formation of GR. Competitive  
binding site of oxyanions and  $\text{Fe}^{\text{II}}$  onto ferric oxide surface was also suggested as a  
factor controlling the nature of the bioreduction product (O'Loughlin *et al.*, 2010) as  
well as the iron reduction rate (Ona-Nguema *et al.*, 2003). In addition, since the  
75 carbonated GR1 is relatively unstable as regards to magnetite (Tronc *et al.*, 1992), it  
has been suggested that the components cited above (phosphate, polymers or  
silicate), could also promote the formation of GR by playing a protective role on the

GR crystals. The sorption of anionic components onto the crystals, especially on the lateral faces, would impair their dissolution and thus their subsequent transformation  
80 into magnetite (Benali *et al.*, 2001; Bocher *et al.*, 2004; Sergent *et al.*, 2010).  
In natural environments, bacteria are usually present in association with complex organic matter, heterogenous and diverse minerals and inorganic particles. For instance, biofilms, which are a widespread form of life for bacteria, are mainly constituted by an arrangement of bacteria embedded in exo-cellular polymeric  
85 substances (EPS) (De Beer and Stoodley, 2006). Thus, since the presence of EPS and large cell densities were identified to be favorable factors for the (bio)mineralization of GR, as afore mentioned, one could expect that biofilms, especially those rich in iron, display a suitable environment for the GR's formation. However, to our knowledge, the formation of GR in a more complex environmental  
90 media or from a biofilm material remains poorly studied. Recently, one study has reported the formation of a GR1 by anaerobic incubation of a ferric material collected from a groundwater seep (Blöthe and Roden, 2009).  
The purpose of this study was therefore to evaluate the potentiality of a biofilm material to promote the formation of GR and other Fe<sup>II</sup> phases. To that end, we used  
95 ferruginous biofilms present in the Sinnamary Estuary (Atlantic Ocean, French Guiana), a well-described mercury contaminated area, due to past and present anthropic activity (Dominique *et al.*, 2007; Muresan *et al.*, 2008). We evaluated the capability of the biofilm components to display an iron reducing activity and to promote the formation of GR especially because of its high reactivity towards  
100 pollutants such as cationic mercury.

## 2. MATERIALS AND METHODS

### 105 2.1. Sites and biofilm sampling

The biofilm samples were collected in the Sinnamary Estuary in French Guiana (Figure 1) where a hydroelectric dam was built in 1994. The resulting reservoir has flooded more than 350 km<sup>2</sup> of tropical rainforest inducing a major disturbances of biogeochemical cycles in both the reservoir and the Sinnamary Estuary downstream the dam (Richard *et al.*, 1997; De Mérona *et al.*, 2005). For example the biodegradation of the huge immersed biomass has led to a significant decrease of the  $E_h$  in the water column, decreasing the O<sub>2</sub> level from 7.2 mg l<sup>-1</sup> in 1992 to 0.4 mg l<sup>-1</sup> just after the dam from 1995 to present (Richard *et al.*, 1997; Dominique, 2006). As a result, the dam effluent water is significantly concentrated in reduced species such as soluble Fe<sup>II</sup> species (up to 15 - 20 μmol l<sup>-1</sup>) (Muresan *et al.*, 2008) and increased by a factor 10 (from 2 μmol l<sup>-1</sup> to 23 μmol l<sup>-1</sup>) after the dam construction (Dominique, 2006). These Fe<sup>II</sup> species are probably the precursor of the red flocs transported by the estuary river and of the thick red-brown slimes recovering any surface in contact with the water up to ~ 30 km after the dam (Figure 2a, b). In addition, the anaerobic conditions occurring in the reservoir contribute to the formation of the methyl mercury in the Sinnamary Estuary (Dominique *et al.*, 2007; Muresan *et al.*, 2008).

The samples were collected between March 2005 and March 2008 at three sampling stations: i) the *Passerelle* station (N5°03'54", W53°03'08"); ii) the *Vénus* station (N5°11'04", 52°58'42") and, iii) the *Estuary* station (N5°26'58", W53°0'21") localized ~ 0.8 km, ~ 20 km and ~ 65 km after the Petit-Saut dam respectively (Figure 1).

The biofilms were collected at the *Passerelle* and *Vénus* stations and the surface sediments at the *Estuary* station. They were collected by scrapping the surfaces (immersed rope, branches, rock) with a sterile spoon and poured into sterile boxes in polypropylene filled with the river water. At the *Estuary*, the surface sediments were mainly sand-like deposit (~ 50 cm depth) in the hollow of a rock. The samples were transported to the laboratory station in an isotherm container (Chest 36QT, Coleman<sup>®</sup>, Wichita, KS) under one to five hours. Aliquot of these samples were stored in refrigerated conditions (isotherm container with ice-pack, around 4°C) during aircraft transportation to the metropolitan laboratory two weeks after the sampling, or were used on site immediately (“freshly used”). When the samples served both as Fe<sup>III</sup> source and inocula they were used directly after their collection; when they served as Fe<sup>III</sup> source only, they were lyophilized after transportation.

## 140 2.2. Biomineralization assays

The biomineralization assays were conducted in three ways (Table 1):

- 145 - Biofilms as Fe<sup>III</sup> source: consisted of anaerobic incubations of lyophilized biofilms supplemented with an electron donor and a cell suspension of an iron reducing bacteria.
  - Biofilms (or surface sediments) as inocula : consisted of incubations of synthetic lepidocrocite ( $\gamma$ -FeOOH, as Fe<sup>III</sup> source) with autochthonous bacteria as inoculum and supplemented with an electron donor.
  - Biofilms as inocula and Fe<sup>III</sup> source : consisted of incubations of the fresh biofilm components just supplemented with electron donors.
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### 2.3. Biofilms as Fe<sup>III</sup> source

Dense resting cell suspensions of *Shewanella putrefaciens* CIP80.40 (Collection of Institut Pasteur, Paris, France) were obtained after a 24 h aerobic culture in tryptcase soy broth (30 g l<sup>-1</sup>, 51019, BioMérieux, Marcy l'Étoile, France) and washed twice (centrifugation 10,000 × g; 10 min; 20°C) with 0.7% NaCl solution. A series of duplicates of 100 ml serum bottles (sealed with thick butyl rubber stoppers, Bellco Glass Inc., Vineland, NJ) were prepared and contained 8.4 10<sup>8</sup> and 3.2 10<sup>9</sup> cells ml<sup>-1</sup> (final concentration) with sodium-formate (NaHCOO) 70 mmol l<sup>-1</sup> as the sole electron donor in a sterile mineral medium in pure water (MilliRO/MilliQ+, Millipore, Billerica) as previously described (Zegeye *et al.*, 2007a): 22 mmol l<sup>-1</sup> NH<sub>4</sub>Cl, 1.5 mmol l<sup>-1</sup> NaCl, 1.2 mmol l<sup>-1</sup> KCl, 1.1 mmol l<sup>-1</sup> MgSO<sub>4</sub>·7H<sub>2</sub>O, 0.71 mmol l<sup>-1</sup> nitrilotriacetic acid, 0.67 mmol l<sup>-1</sup> CaCl<sub>2</sub>, 0.27 mmol l<sup>-1</sup> MnSO<sub>4</sub>·H<sub>2</sub>O, 133 μmol l<sup>-1</sup> anthraquinone disulfonate (ADQS), 86 μmol l<sup>-1</sup> ZnCl<sub>2</sub>, 38 μmol l<sup>-1</sup> CoSO<sub>4</sub>·7H<sub>2</sub>O, 32 μmol l<sup>-1</sup> FeSO<sub>4</sub>·7H<sub>2</sub>O, 9.3 μmol l<sup>-1</sup> Na<sub>2</sub>MoO<sub>4</sub>·2 H<sub>2</sub>O, 9.1 μmol l<sup>-1</sup> NiCl<sub>2</sub>·6H<sub>2</sub>O, 6.8 μmol l<sup>-1</sup> Na<sub>2</sub>WO<sub>4</sub>·2H<sub>2</sub>O, 3.6 μmol l<sup>-1</sup> CuSO<sub>4</sub>·5H<sub>2</sub>O, 1.9 μmol l<sup>-1</sup> AlK(SO<sub>4</sub>)<sub>2</sub>·12H<sub>2</sub>O, 1.5 μmol l<sup>-1</sup> H<sub>3</sub>BO<sub>3</sub>. Finally, 25 g l<sup>-1</sup> of the lyophilized biofilm were added. The Fe<sup>III</sup> present in this biofilm (170 mmol l<sup>-1</sup> Fe<sup>III</sup> equivalent) was assumed to be the sole electron acceptor. This lyophilized biofilm extract was not heat sterilized in order to avoid any modifications of the iron oxide minerals. All other constituents than lyophilized biofilm and *Shewanella* cells have been heat sterilized, except formate and AQDS which were sterilized by filtration. A control was done in the same conditions except that no resting cells of *S. putrefaciens* was added.

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#### 2.4. Biofilms as inocula

One ml of a biofilm suspension collected at *Passerelle* and *Vénus* stations, or from surface sediment (*Estuary* station), served as inoculum for 9 ml of the following anaerobic culture medium (final concentration in purified water): suspension of 5.3 g l<sup>-1</sup>  $\gamma$ -FeOOH (i.e. : 60 mmol l<sup>-1</sup> equiv. Fe<sup>III</sup>) as electron acceptor; 5 mmol l<sup>-1</sup> sodium formate, 5 mmol l<sup>-1</sup> sodium acetate, 2.5 mmol l<sup>-1</sup> sodium lactate as electron donor mix. The basal and mineral medium contained (final concentration in pure water): 30 mmol l<sup>-1</sup> NaHCO<sub>3</sub>, 4.5 mmol l<sup>-1</sup> NH<sub>4</sub>Cl, 4 mmol l<sup>-1</sup> NaH<sub>2</sub>PO<sub>4</sub> H<sub>2</sub>O, 1.3 mmol l<sup>-1</sup> KCl, 0.1 mmol l<sup>-1</sup> MgSO<sub>4</sub>, 30  $\mu$ mol l<sup>-1</sup> MnSO<sub>4</sub>, 8  $\mu$ mol l<sup>-1</sup> CoSO<sub>4</sub>, 7  $\mu$ mol l<sup>-1</sup> CaCl<sub>2</sub>, 7  $\mu$ mol l<sup>-1</sup> ZnSO<sub>4</sub>, 1.5  $\mu$ mol l<sup>-1</sup> H<sub>3</sub>BO<sub>3</sub>, 1  $\mu$ mol l<sup>-1</sup> Na<sub>2</sub>SeO<sub>4</sub>, 1  $\mu$ mol l<sup>-1</sup> NiCl<sub>2</sub>• 6H<sub>2</sub>O, 0.7  $\mu$ mol l<sup>-1</sup> Na<sub>2</sub>WO<sub>4</sub>• 2 H<sub>2</sub>O, 0.5  $\mu$ mol l<sup>-1</sup> Na<sub>2</sub>MoO<sub>4</sub>• 2 H<sub>2</sub>O, 0.4  $\mu$ mol l<sup>-1</sup> CuSO<sub>4</sub>, 0.3  $\mu$ mol l<sup>-1</sup> AlK(SO<sub>4</sub>)<sub>2</sub>• 12 H<sub>2</sub>O. AQDS (100  $\mu$ mol l<sup>-1</sup>) were added with the mix of electron donors, previously sterilized by filtration into the autoclaved medium. Vitamins were added from filtered sterilized stock solutions containing (in final concentration) 20  $\mu$ g l<sup>-1</sup> biotin, 20  $\mu$ g l<sup>-1</sup> folic acid, 100  $\mu$ g l<sup>-1</sup> pyridoxine HCl, 50  $\mu$ g l<sup>-1</sup> riboflavin, 50  $\mu$ g l<sup>-1</sup> thiamine, 50  $\mu$ g l<sup>-1</sup> nicotinic acid, 50  $\mu$ g l<sup>-1</sup> pantothenic acid, 1  $\mu$ g l<sup>-1</sup> B-12, 50  $\mu$ g l<sup>-1</sup> para-aminobenzoic acid, and 50  $\mu$ g l<sup>-1</sup> thiotic acid. The lepidocrocite was chemically synthesized according to the method described by Zegeye *et al.* (2007a). Lepidocrocite was preferentially chosen due to its stability during the heat sterilization of the medium but also because this mineral was suitable for GR biomineralization (Ona-Nguema *et al.*, 2002) and finally because it was identified, as it will be indicated below in the manuscript, to be the main mineral constituting the present ferruginous biofilm.

### 2.5. Biofilms as inocula and Fe<sup>III</sup> source

Freshly harvested biofilms from *Passerelle* station were poured into 100 ml serum bottles filled with the Sinnamary Estuary water (composition described in Table 2).

205 The suspension obtained was supplemented with 10 – 30 ml of a mix of electron donors in different proportions (Table 1). It was assumed that the biofilm components provided the Fe<sup>III</sup> as the main electron acceptor. At the start of the experiments, the Fe<sup>III</sup> amount in the biofilm was not measured yet, therefore three ratio of electron donor mix / biofilm suspension were tested. The determination of Fe later on  
210 indicated that on the one hand two assays contained 22 and 31 mmol l<sup>-1</sup> of Fe<sup>III</sup> with an electron donor concentration of 4, 4, and 2 mmol l<sup>-1</sup> for acetate, formate and lactate respectively; and on the other hand the third assay contained 57 mmol l<sup>-1</sup> of Fe<sup>III</sup> with an electron donor concentration of 15, 15, and 7.5 mmol l<sup>-1</sup> for acetate, formate and lactate respectively (Table 1).

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All incubation media were purged with O<sub>2</sub>-free N<sub>2</sub>(99.99%) gas for 30 min in aseptic condition. All the assays displayed a pH of 6.5±0.2 and were incubated at 30°C in the dark.

### 220 2.6. Analytical techniques

The dry weight (DW) of the biofilm samples were measured in the Hydreco Laboratory facilities (Kourou, French Guyana) few hours after sampling. The weight of a desiccated pellets was measured from a 10 ml biofilm suspension centrifuged for  
225 5 min at 10,000 × *g* and dried at 105°C over night. The ash content was measured

after 3 h of calcination (550°C) and the ash free dry weight was then calculated by difference. The total iron content (mg g<sup>-1</sup> DW) has been performed by ICP-AES after acidic digestion in HCl 6 N.

230 The Fe<sup>III</sup> reduction was monitored by measuring the Fe<sup>II</sup> accumulation over time. The amount of total Fe<sup>II</sup> (*i.e.* in the solid and soluble phases) extracted by HCl 5 mol l<sup>-1</sup> was determined with ortho-phenanthroline (Fadrus and Maly, 1975). The soluble Fe<sup>II</sup> was assessed after filtration through 0.2 μm membrane filter (Millex-GP SLGP, Millipore, Billerica, MA) in an anaerobic chamber (N<sub>2</sub>/H<sub>2</sub>, 97/3, Coy Laboratory Product Inc., Grass Lake, MI, USA).

235 The cell numbers were determined by the epifluorescence microscopy technique using the SYBR green I fluorochrome as a dye (Invitrogen) on the biofilm suspension, previously dispersed by ultrasonic bath treatment (15 min, 120 W, RK31, 35KHz, Sonoclean, Paris, France).

## 240 2.7. Solid analysis

Surface elemental composition of the lyophilized biofilm has been determined by X-ray photoelectron spectroscopy (XPS). XPS spectra were recorded using a KRATOS Axis Ultra spectrometer instrument with a monochromatic Al K<sub>α</sub> Xray (hν = 1486.6 eV) with the same procedure and apparatus than Zegeye *et al.* (2007b).

245 The solids were also characterized by X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), Raman spectroscopy (RS), and Mössbauer spectroscopy (MS). The XRD data were collected with a D8 Bruker diffractometer, equipped with a scintillator detector. The X-ray source was a Co

250 anode ( $\lambda = 0.17902$  nm). The diffractograms were recorded in the  $3 - 64^\circ 2\theta$  range, with a  $0.035^\circ$  step size and a collecting time of 3 seconds per point.

The suspension was filtered under  $N_2$  atmosphere, mixed with glycerol to avoid oxidation and placed on a sample carrier to be analyzed by XRD.

For TEM observation, one drop of the suspension was laid on an amorphous carbon-coated grid and the sample was loaded into the microscope (Philips CM20/STEM).  
255

The relative element composition of the analyzed solids was obtained by energy dispersive X-ray analysis (EDX). For the scanning electronic microscopy (SEM) examination, one drop of the sample was sprinkled onto  $2\text{ cm}^2$  plates and examined under vacuum (Hitachi 54800 Scanning Electron Microscopy).

260 A Raman characterization was performed with a special cell used for Raman experiments. The sample was set under an  $N_2$ - $O_2$  free atmosphere in an anaerobic chamber and the cell was tightly closed by a glass window through which a laser beam was focused and the Raman backscattering collected. The cell is mounted in the focal plane of an Olympus B.H. microscope in a Jobin-Yvon/Instrument S.A. T  
265 64000 Raman microprobe equipped with charged coupled device detector and a motorized X-Y stage. A large working distance objective length of 50 x magnification was used. A 514.53 nm exciting radiation was used with a power  $\sim 0.2$  mW to prevent sample degradation. The spectra resolution was about of  $6\text{ cm}^{-1}$  and the precision on the wavenumber was  $1\text{ cm}^{-1}$ . Two successive scan of 90 s were performed.

270 The Mössbauer spectroscopy (MS) was performed from 12 to 295 K with a closed helium cycle variable temperature Mössbauer cryostat equipped with vibration isolation stand manufactured by Advanced Research Systems (ARS), utilizing a constant acceleration Mössbauer spectrometer with a 50 mCi source of  $^{57}\text{Co}$  in Rh

and calibrated with a 25  $\mu\text{m}$  thick  $\alpha\text{-Fe}$  foil at ambient temperature. Spectra were  
275 fitted using Lorentzian-shape lines and parameters were mathematically  
(minimization of  $\chi^2$ ) and physically significant.

### *2.8. Microscopy for cells and biofilm matrix observations*

280 The embedding technique previously described by Droppo *et al.* (1996) has been  
modified and adapted to the ferruginous biofilms. Briefly, freshly handled fragments  
of biofilms with their substrata (nylon rope) were poured into 10 ml of estuarine water  
containing 4 % of glutaraldehyde. After the settlement of the fragments ( $\sim 2$  h), the  
supernatant was gently removed and replaced by a solution of low-melting-point  
285 electrophoresis grade and sterile agarose (0.75 %). After solidification (and  
transportation until the metropolitan laboratory in isotherm boxes) the samples were  
dewatered in ethanol and in propylene oxide, and embedded in epoxy resin. Finally,  
thin and ultra-thin sections were stained with Azur blue II or lead nitrate respectively  
prior to examination with the optical microscopy or TEM respectively.

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## **3. Results**

### *3.1. Characterization of the ferruginous biofilms*

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The biofilm recovering all surfaces in contact with the water of the Sinnamary Estuary  
appeared as a brown-orange color gluying slime (Figure 2a, b) being in some areas  
up to  $\sim 1$  cm thick. As expected, iron was the major inorganic part of the biofilms from  
*Passerelle* and *Vénus* stations and accounted for 0.37 and 0.20  $\text{g g}^{-1}$  of the dry

300 weight according to ICP-AES analysis, respectively (Table 2). The XPS analysis confirmed the presence of an important amount of iron into the biofilm. The oxide component located at 530.9 eV in the O<sub>1s</sub> spectrum (Table SI-1) indicated that the iron was involved in a ferric oxide phase. The organic matter represented approx. 35 % of the DW part of the ash free dry weight measure (Table 2). In addition to oxygen, 305 the significant amount of N, C and S was in agreement with the presence of organic matter. Optical microscopic observation indicated the presence of copious amount of various microorganisms like diatoms (not shown) and bacterial colonies embedded in an organic or Fe-bearing gel like matrix (Figure 2c). Iron oxides were present in close vicinity to bacterial cells (Figure 2d).

310 The Table 2 indicates that microbial cells accounted for a significant part of the biofilm constituents with  $1.3 - 6 \times 10^{11}$  cells g<sup>-1</sup> DW. According to their composition these biofilms can be well qualified as a ferruginous one.

TEM and XRD analyses of the inorganic phases indicated amorphous or slightly diffracting materials. Two Fe-phases were discerned. The first one showed a 315 “crumpled paper” like structure, and gave an electron diffraction pattern consistent with the lepidocrocite ( $\gamma$ -FeOOH) (Fig. 2e and Table SI-2). The X-ray diffraction pattern exhibited the major band specific to SiO<sub>2</sub> but also very broad bands localized in the same area of those of lepidocrocite and in a lower trend of ferrihydrite (Fig. 3a). The second Fe-phase did not display a diffraction spectrum with the electron beam 320 and exhibited a granular trend (Fig. 2f). Fe and O were the major elements of those two phases, along with Si, Al, Na, and Cl in a lower amount according to EDX analysis (not shown). The presence of both  $\gamma$ -FeOOH and ferrihydrite was in agreement with Raman spectroscopy analyses. The spectrum of the lyophilized

biofilm (spectra *a* in Fig. 3b) shows band at  $250\text{ cm}^{-1}$ , a broad band in the area of  $375$   
325  $\text{cm}^{-1}$  and a very broad band in the area of  $700\text{ cm}^{-1}$  matching well with the spectra of  
synthetic lepidocrocite and ferrihydrite (spectra *c* and *b*, respectively) (Fig. 3b).  
The room temperature Mössbauer spectrum of the ferruginous biofilms exhibited a  
broadened doublet, which can be fitted reasonably with two paramagnetic  
quadrupole components  $D_L$  and  $D_F$  (Fig. SI-3). The two doublets were distinct in their  
330 quadrupole splittings (0.55 and 0.91) whereas their isomer shifts were identical.  
According to the literature, the component  $D_L$  (Table SI-3) characterized by the  
isomer shift of 0.33 and the quadrupole splitting of 0.55 mm/s corresponds to  
lepidocrocite (Murad and Schwertmann, 1984). The other component  $D_F$ , with the  
same isomer shift (0.35 mm/s), and a larger quadrupole splitting of 0.91 mm/s  
335 characterizes ferrihydrite. The Mössbauer spectroscopy confirmed therefore that  
lepidocrocite and ferrihydrite were the main  $\text{Fe}^{\text{III}}$  oxides of the biofilm. In addition, it  
enlighten that lepidocrocite and ferrihydrite contributed to  $3/4$  (74 %) and  $1/4$  (26 %) of  
the whole solid Fe phase, respectively (Table SI-3).

### 340 3.2. Bioreduction of $\text{Fe}^{\text{III}}$ material

Up to 63 % of the lyophilized ferruginous biofilm's  $\text{Fe}^{\text{III}}$  were reduced by *S.*  
*putrefaciens* after 70 days of incubation (Table 1 and Fig. 4). After 800 days, the  
amount of  $\text{Fe}^{\text{II}}$  formed did not change indicating that the equilibrium in term of  $\text{Fe}^{\text{II}}$   
345 level was attained after 70 days. A slight  $\text{Fe}^{\text{III}}$  reduction was noted in the control  
(without *Shewanella* cells) (Fig. 4) probably due to a residual activity of iron reducing  
bacteria in the lyophilized sample. This was supported by the growth of some  
colonies in anaerobic as well as in aerobic incubation on solid medium (TS agar) (not

shown). Thus, it indicates that at least 2/3 of the total Fe was available for  
350 bioreduction. In addition, no significant difference, in terms of iron reduction extent  
and initial iron reduction rate ( $16 \pm 4 \text{ mmol l}^{-1} \text{ day}^{-1}$ , from data of Fig. 4 fitted as a first  
order kinetic) was clearly evidenced between the assays containing  $8.4 \times 10^8 \text{ cells ml}^{-1}$   
(named LC for “low” cell density) and those with  $3.2 \times 10^9 \text{ cells ml}^{-1}$  (named HC for  
“high” cell density) (Fig. 4).

355 The “aqueous  $\text{Fe}^{\text{II}}$ ” ( $< 0.2 \mu\text{M}$ ) was very low in all samples ( $< 20 \mu\text{mol l}^{-1}$ ) (at 70 days)  
clearly indicating that  $\text{Fe}^{\text{II}}$  was mainly under a solid state.

### *3.3. Ability of autochthonous cells to reduce iron oxide*

360 After six months of incubation time, up to 39% of  $\gamma\text{-FeOOH}$  were reduced by the  
biofilm (*Passerelle* and *Vénus*) and the surface sediment (*Estuary*) aliquots indicating  
the presence of iron reducing bacteria in those samples (Table 1). The anaerobic  
incubation of the freshly sampled biofilm supplemented with electron donor mix (that  
is to say the fresh biofilm served both as iron oxide and iron reducing bacteria  
365 sources), revealed the reduction of  $59 \pm 6\%$  of the ferric oxides after 180 days (Table  
1). An increase of nearly two units of pH was noted (6.5 to 8.5, Table 1) as it is  
usually observed during the  $\text{Fe}^{\text{III}}$  reduction in weakly buffered medium (Ona-Nguema  
*et al.*, 2002; Zegeye *et al.*, 2007a).

Therefore, the biofilms and surface sediment samples exhibited an efficient iron  
370 reducing activity to reduce up to 2/3 of the endogenous  $\text{Fe}^{\text{III}}$  or exogenic iron oxide  
(synthetic lepidocrocite).

### 3.4. Characterization of the secondary iron minerals

375 The analysis by XRD and TEM of the solid phase clearly indicated the presence of GR1 in both the incubation assays when the biofilm served as Fe<sup>III</sup> source (lyophilized biofilm inoculated with *S. putrefaciens*) and as inocula (synthetic lepidocrocite inoculated with 10% v/v fresh sample extract) (Table 1).

In the first case the GR1 was identified by XRD, TEM and MS after 70 and 800 days  
380 of incubation as the major solid Fe phase for the two cell concentrations tested. XRD displayed no other characteristic and significant peaks, except a weak one for magnetite, than those of the GR1 after 70 days (Fig. 5) indicating that the GR1 was the major ferrous crystalline phase. However, in the LC (low cell density) assays, the GR1 signal intensity appeared lower suggesting a poor crystallinity of the solids in  
385 those samples. After 800 days of incubation, the GR1 still remained the major crystalline phase (at a level discernable by XRD) despite of a stronger signal intensities for the magnetite and the apparition of a calcium magnesium iron carbonate. In the control, no significant peak was detected (Fig. 5). The TEM examination showed crystals with a rounded shape (Fig. 6a), and by SEM they  
390 looked-like amorphized GR platelet (Fig. 6b). Those crystals exhibited a diffraction pattern characteristic of the GR1 (Fig. 6a and Table SI-4). The Mössbauer spectrum at room temperature (Fig. SI-3) displayed a mixture of a component (four doublets in the center of the spectrum) in a paramagnetic state and at higher energy, two sextets S<sub>1</sub> and S<sub>2</sub> in magnetically ordered states. Theses sextets were attributed respectively  
395 to iron in tetrahedral (Fe<sup>3+</sup>) and octahedral (Fe<sup>2.5+</sup>) sites in the magnetite crystal. The intensity ratio between S<sub>1</sub> and S<sub>2</sub> of about 2 concurred likely with a stoichiometric magnetite. The four doublets obtained in the center of the spectrum correspond to

two Fe<sup>2+</sup> doublets (large values of quadrupole splitting and isomer shift) and to two Fe<sup>3+</sup> doublets (small value of quadrupole splitting and isomer shift). The hyperfine parameters (Table SI-5) confirmed the presence of the GR in this sample (Refait *et al.*, 2006), thus supporting the diffraction results (XRD and TEM). The Mössbauer spectroscopy confirmed also the presence of another Fe<sup>II</sup> bearing mineral (probably the calcium magnesium iron carbonate) and indicated a remaining of Fe<sup>III</sup> source. The three phases, GR, magnetite and calcium magnesium iron carbonate counted for 405 60%, 20% and 13% of the total iron respectively. The fourth phase, the residual lepidocrocite, accounted for 7% (Table SI-5).

In the second case (assays with biofilms as inocula for synthetic lepidocrocite reduction), some GR crystals were observed by optical microscopy or by TEM examination (Fig. 6c&d) and XRD analysis confirms the presence of GR phase with 410 vivianite (Fe<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>•8H<sub>2</sub>O) (Fig. SI-4) due likely to the presence of phosphate in the culture medium.

The observation by optical microscopy of the solids from the incubation with biofilm serving both as electron acceptor and inoculum, showed several green rust-like colored particles (Fig. 6f). In order to discriminate those particles with cell-bearing 415 chlorophyll, the suspension was examined under UV light. Some green particles were red fluorescent corresponding to photosynthetic cells, but other green particles were non-fluorescent under UV light excluding the fact that they correspond to cell-containing chlorophyll. Particles exhibiting the same size (~ 1 μm) were observed under TEM. They gave an electronic diffraction pattern corresponding to an 420 hexagonal symmetry (Fig. 6e) and the other 1.6 time higher than the d<sub>hkl</sub> {101} exhibiting (0.441 nm against 0.272). TEM-EDX indicated that these particles were

constituted by  $34\pm 2\%$  and  $66\pm 2\%$  of Fe and O, respectively. However, the other solid analysis methods, like XRD, Raman spectroscopy or MS, did not provide any exploitable results due probably to the low amount of samples in the assays.

425

## 4. Discussion

### 4.1. Ferric iron oxides and bacteria in the biofilm

430 A growing body of literature indicates that biofilm materials, cell surface appendages or exo-polymeric substances contribute significantly to the secondary iron biomineralization (Ferris et al., 1986; Brown et al., 1994; Brown et al., 1998; Salas *et al.*, 2010). The most accepted mechanism is that cell surface could play the role of nucleation center to initiate the crystal formation. In addition, specific cellular  
435 metabolism could also be involved acting as iron oxidizer or reducer. The biofilms developing in the Sinnamary Estuary, would then present a suitable environment for such mineralization processes. They are indeed mainly constituted of iron (30-40% of the DW) and microbial cells. The two iron oxides identified in these biofilms, lepidocrocite and ferrihydrite, could result from physico-chemical reactions or be  
440 induced by bacterial activity. The ferrihydrite is a widespread iron oxide and also precipitates in the vicinity of iron oxidizing bacteria (Fortin and Langley, 2005). Lepidocrocite on the other hand, is a relatively scarce iron oxide, it has however a widespread occurrence in suboxic environment such as reductomorphic soils and it is a typical oxidation product of GR (Schwertmann and Taylor, 1989). It was also shown  
445 to be the main product of Fe<sup>II</sup>-oxidizing nitrate reducing bacteria (Larese-Casanova *et al.*, 2010).

In the biofilms used in the present work, the lepidocrocite exhibited low sized crystals and a weak cristallinity (according to the broad XRD peaks) and the ferrihydrite was not detected by XRD. Such characteristics are typical of natural iron oxides  
450 associated with high organic matter, especially for the bacteriogenic ferric iron oxides resulting from a rapid Fe<sup>II</sup> oxidation (Schwertmann and Taylor, 1989 ; Fortin and Langlet, 2005). Moreover, twisted like structures (Fig. SI-5) suggest the presence of *Gallionella* sp., a ferrous oxidizing bacteria genous (Ghiorse and Ehrlich, 1992). The low acidic pH (~ 6.5) and the significant level of Fe<sup>2+</sup> occurring in the Sinnamary  
455 estuarine water are also favorable conditions for near-neutral iron oxidizing bacteria (Søgaard *et al.*, 2000 ; Blöthe an Roden, 2009). The bacteria are embedded into an EPS matrix and are in close contact with iron solids supporting the hypothesis of a direct interaction between bacteria and iron oxides. These iron oxides could be the by-product of iron oxidizing bacteria, and could also serve as final electron acceptor  
460 for DIRB (Straub *et al.*, 1998). Indeed, the iron reducing bacteria were estimated to represent up to 10<sup>8</sup> cells g<sup>-1</sup> in those biofilms (Huguet *et al.*, 2010). As it is usually observed for mature biofilms or bacterial aggregates, the aerobic metabolism of bacteria could significantly affect the redox potential and create strong anaerobic conditions few dozen or hundred  $\mu\text{m}$  within a biofilm (Stewart and Franklin, 2008)  
465 which would allow the anaerobic respiration of Fe<sup>III</sup> and subsequently the formation and the stability of secondary Fe<sup>II</sup>-bearing minerals. The possibility that bacterial Fe<sup>II</sup> oxidation and Fe<sup>III</sup> reduction could be tightly coupled in such environments have been suggested and documented (Emerson and Mayer, 1997; Sobolev and Roden, 2002; Blöthe and Roden, 2009).

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#### 4.2. Iron reduction and GR biomineralization

In order to evaluate the capability of biofilm's iron oxides to be transformed into secondary iron minerals, lyophilized biofilm were used as electron acceptor for *S. putrefaciens*, a bacteria well-known to precipitate GR from lepidocrocite or ferrihydrite bioreduction. The iron reduction rates ( $0.7 \pm 0.1 \text{ mmol l}^{-1} \text{ h}^{-1}$  from data of Fig. 4) of the ferric material present in the Sinnamary biofilm were in the same order of magnitude comparatively to other studies performed in similar conditions in terms of cells/ $\text{Fe}^{\text{III}}$  ratio and formate concentration (iron reduction rate varied from  $\sim 0.1$  to  $15 \text{ mmol L}^{-1} \text{ h}^{-1}$ , Ona-Nguema *et al.*, 2002 ; Zegeye *et al.*, 2007a; O'Loughlin *et al.*, 2007; O'Loughlin *et al.*, 2010; Zegeye *et al.*, 2010). This indicates that the ferric oxides of the biofilms from the Sinnamary River were readily available for bacterial reduction. Indeed, as regards to the proportion of  $\text{Fe}^{\text{III}}$  reduced, the ferric biofilm material appeared to be more reducible than the synthetic iron oxide (Table 1). This was also noted from previous studies with natural ferric material from another origin (Straub *et al.*, 1998; Blöthe and Roden, 2009). The GR1 (assumed to be the  $\text{GR}(\text{CO}_3^{2-})$ ) was the main secondary mineral produced by the bacterial reduction of the biofilm's iron oxide by *S. putrefaciens*. It has been previously shown that *S. putrefaciens* CIP 80.40 promotes the GR biomineralization under a high ratio cell density/iron oxide (above  $10^{10} \text{ mmol}^{-1}$ ) (Zegeye *et al.*, 2007a; Zegeye *et al.*, 2010). At a lower ratio cells/ $\text{Fe}^{\text{III}}$  and in absence of significant amount of phosphate or silica, magnetite ( $\text{Fe}_3\text{O}_4$ ) was the main secondary mineral expected as regards to literature data (Fredrickson *et al.*, 1998; Ona-Nguema *et al.*, 2002; Kukkadapu *et al.*, 2004; Zegeye *et al.*, 2007a; Zegeye *et al.*, 2010; Sergent *et al.*, 2010). In the present work, whatever the ratio used, below ( $0.5 \times 10^{10} \text{ mmol}^{-1}$ ) or above ( $2 \times 10^{10} \text{ mmol}^{-1}$ ), the GR was the dominant

secondary iron mineral with minor magnetite formation as indicated by Mössbauer analysis. This indicates that the lyophilized biofilm promotes the GR1 instead of magnetite. The lyophilized biofilm contains a large proportion of organic matter like cellular wastes and probably exo-cellular polymers. Thus, in previous works, it was shown that autoclaved cells, EPS or organic polymers promote the GR precipitation (Zegeye *et al.*, 2007a; Jorand *et al.*, 2008; O'Loughlin *et al.*, 2010). Flocculation and bacterial strains have been also suggested to influence the GR precipitation (Salas *et al.*, 2010; Zegeye *et al.*, 2010). Similar results concerning the secondary mineral were obtained from ferruginous biofilm ("layered natural ferric precipitates") collected from a groundwater seep (Blöthe and Roden, 2009). Therefore, ferruginous biofilms like those found into the Sinnamary Estuary are expected to be favorable for the precipitation of GR since they exhibit EPS and large cell density in a close volume.

#### 4.3. Green rust ageing and stabilization

The stability of carbonated GR1 is known to be very weak in the absence of stabilizing agents like phosphate, microbial cell suspension, or silicate and is readily transformed, within few hours, into magnetite (Benali *et al.*, 2001; Bocher, *et al.*, 2004; Kukkadapu *et al.*, 2005). The XRD analysis of aged incubation samples at 30°C in darkness during 800 d (~ 2 years) showed that the GR1 is still present after a long period of time in the medium, indicating the relative stability of the mineral in those conditions. Only a minor fraction of GR was partially transformed into magnetite and/or calcium magnesium ferrous carbonate. This suggest that the biofilms or the medium (e.g. : phosphate in that case) have provided some materials inducing the stabilization of the GR1.

It is wellknown that the GR is readily produced from  $\gamma$ -FeOOH bioreduction in batch experiment with a large cell density of pure strain *Shewanella* sp. (resting cells). This has been also shown by this work with environmental iron oxides. But when the cell density was lower, i.e. in order to initiate a cell growth or to start with a cell density closer to that found in natural environments (i.e.  $< 10^8$  cells mL<sup>-1</sup>), the extent of the Fe<sup>III</sup> reduction was generally very low and the number of cultivable cells declined with the time (e.g. : Roden and Urrutia, 2002). For such studies, the final product was mainly the magnetite (e.g. : Lovley *et al.*, 1987; Glasauer *et al.*, 2003). However, it was reported by Blöthe and Roden (2009) and from the present study, that the formation of GR1 occurred from environmental sample where the Fe oxide appears to be associated with organic phases. The key role of the organic phases would proceed by stabilizing the GR1 or by initiating its formation instead of another Fe<sup>II</sup> bearing mineral.

The organic material associated with the biofilm as well as constituents such as humic-like substances, quartz particles could contribute to GR occurrence as it was suggested by laboratory experiments (O'Loughlin *et al.*, 2010; Sergent *et al.*, 2010). These hypothesis need however to be supported by more data on the nature of the dominate members of the microbial community responsible for the Fe<sup>III</sup> reduction and for the GR formation.

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#### *4.4. GR occurrency in Sinnamary Estuary and biofilms*

The formation of Fe<sup>II</sup>-bearing minerals, especially the GR mineral can be expected in the biofilm of the Sinnamary river since several conditions are gathered to allow its synthesis: presence of DIRB activity into the biofilm, a readily reducible ferric oxides.

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Moreover, the pH interval of the Estuary water is close to the pH (H<sub>2</sub>O) of the hydromorphic soils where the GR mineral (fougerite) has been identified (Bourrié *et al.*, 1999). However, the mineral has not been yet detected directly in the raw biofilm. One can hypothesize that the GR could be present at very low concentration, below the detection level, or it was oxidized during sampling and/or transportation. The causes could be a lack of electron donor or/and a too high O<sub>2</sub> level. Nevertheless, the ferric materials and bacteria constituting these biofilms can potentially support the biomineralization of such interesting mineral serving as electron donor for oxidized chemicals. By extension, one can assume that biofilm could represent an efficient substrate for GR formation. One could speculate that in mercury contaminated area such as the Sinnamary Estuary, the GR has to be taken into account as a potential abiotic mercury attenuation mean of the water phase.

## 5. Conclusions

The anaerobic incubation of ferruginous biofilm components with a pool of electron donor can lead to the formation of the Fe<sup>II</sup>-Fe<sup>III</sup> hydroxysalt green rust from the activity of iron reducing bacteria. In addition, this green rust exhibited a great stability (over than three years in the batch incubation) in the aqueous suspension probably due to the polymeric materials which contribute likely to its stability. The biofilms, such those found in the anthropised Sinnamary Estuary in French Guyana, should therefore be considered as a favorable location for GR biomineralization when redox conditions and electron donors availability are gathered. The presence of this mineral is expected to be in anaerobic pockets within the biofilms, and dedicated analysis on fresh biofilms, preserved from air oxidation, could be conducted to support this

570 hypothesis. Moreover, this ferrous mineral could also serve as Fe<sup>II</sup> source for iron  
oxidizing bacteria and thus be involved in a cycling of iron at a microscopic scale.  
Finally, if the presence of green rust in such biofilm is confirmed, it would contribute  
to the mercury attenuation, which is a pollutant of a major concern in the Sinnamary  
Estuary, by reducing the Hg<sup>II</sup> into the volatile Hg<sup>0</sup>.

575

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755

**Table 1.** Characteristics of the incubation flasks for the biomineralization tests and secondary iron minerals resulting of the DIRB activity at 30°C.  $\pm$ SD are calculated from duplicate or triplicate incubation flasks or from duplicate analysis on a single sample. Since no detectable Fe<sup>II</sup> was present in the raw biofilm sample, Fe<sub>tot</sub> is assumed to correspond to Fe<sup>III</sup>.

Main electron acceptor	Biofilms as Fe <sup>III</sup> source (n=2)			Biofilms as inocula (n=3)			Biofilms as inocula and Fe <sup>III</sup> sources (n=3)
Fe <sub>tot</sub> (Fe <sup>III</sup> ) mmol l <sup>-1</sup>	170 mmol l <sup>-1</sup> (lyophilized biofilm)			60 mmol l <sup>-1</sup> (synthetic $\gamma$ -FeOOH)			22, 31 and 57 mmol l <sup>-1</sup> (freshly sampled biofilm)
Electron donor(s) (mmol l <sup>-1</sup> )	Formate 70			Acetate/formate/lactate 5/5/2.5			Acetate/formate/lactate 4/4/2 or 15/15/7.5
pH (initial)	~ 6.5			~ 6.5			~ 6.5
Inoculum	<i>S. putrefaciens</i>			Biofilm from <i>Passerelle</i> <sup>2</sup>	Biofilm aliquot from <i>Vénus</i> <sup>2</sup>	Biofilm from <i>Estuary</i> <sup>2</sup>	Biofilm suspension (from <i>Passerelle</i> ) <sup>3</sup>
Initial cell density (cells mL <sup>-1</sup> )	8.4 10 <sup>8</sup>	3.2 10 <sup>9</sup>	(Control <sup>1</sup> )	~ 10 <sup>8</sup>	~ 10 <sup>8</sup>	~ 10 <sup>8</sup>	2 – 5 × 10 <sup>9</sup>
Ratio cells/Fe <sup>III</sup> (cells mmol <sup>-1</sup> )	0.5×10 <sup>10</sup>	1.9×10 <sup>10</sup>	/	~ 0.2×10 <sup>10</sup>	~ 0.2×10 <sup>10</sup>	~ 0.2×10 <sup>10</sup>	~ 9×10 <sup>10</sup>
pH (final)	8.5±0.1	8.5±0.1	nd	nd	nd	nd	8.2±0.1
Max Fe <sup>II</sup> % Fe <sup>tot</sup>	51±7%	63±4%	9.4±0.1%	28±1%	39±2%	35.3±0.2%	59±6%
Secondary iron minerals (70 to ~ 800 d)	GR1 M and CMC (traces)	GR1 M and CMC (traces)	Amorphous solids	Amorphous solids with GR like particles	Amorphous solids with GR like particles	GR1 and vivianite	Amorphous solids with GR like particles

<sup>1</sup>no cell amended.

<sup>2</sup>these inocula consisted by suspensions from biofilms or deposits diluted in the estuarine water, 10 % (V/V) of these suspensions were used as inocula.

<sup>3</sup>60 – 90 % (V/V) of a biofilm suspension. nd = not determined.

5

**Table 2.** Physico-chemical characteristics of the water phase and of the ferruginous biofilms at the river stations *Passerelle* and *Vénus* (collected in June 2007). DW = dry weight, AFDW = ash free dry weight, nd = not determined.

Parameters	Station	
	<i>Passerelle</i>	<i>Vénus</i>
<u>Estuarine water<sup>a</sup></u>		
pH	5.8	5.6
O <sub>2</sub> mg l <sup>-1</sup> (%)	5.1 (65)	4.5 (58)
E <sub>h</sub> mV	243 - 321	
PO <sub>4</sub> <sup>3-</sup> μg l <sup>-1</sup>	16.5	17.8
NH <sub>4</sub> <sup>+</sup> μg l <sup>-1</sup>	159	152
Fe <sup>II</sup> <sub>aq</sub> μg l <sup>-1</sup>	922 (~ 16 μmol l <sup>-1</sup> )	536 (~ 10 μmol l <sup>-1</sup> )
Temp °C	26.8 – 28.3	
<u>Biofilms</u>		
DW (g m <sup>-2</sup> ) <sup>b</sup>	30 – 40 <sup>b</sup>	nd
AFDW (% DW)	35 ± 4 (n = 16)	34 ± 4 (n = 3)
Fe (g g <sup>-1</sup> DW) <sup>c</sup>	0.37 ± 0.01 (n = 3)	0.20 ± 0.01 (n = 3)
Fe <sup>d</sup>	8 – 13 % (26 – 38 %)	nd
O (O <sub>2</sub> , R-OH, H <sub>2</sub> O) <sup>d</sup>	33 – 35 % (27 – 33 %)	nd
N (-NH <sub>2</sub> , NH <sub>2</sub> <sup>+</sup> ) <sup>d</sup>	2.6 – 2.7 % (1.9 – 2.2 %)	nd
C (-C, H ; C-O, H ; C=O) <sup>d</sup>	51 – 54 % (32 – 38 %)	nd
S (R-S-, S <sup>2-</sup> ...) <sup>d</sup>	0.17 – 0.18 % (0.28 – 0.33 %)	nd
Bacteria (cells g <sup>-1</sup> DW)	6 ± 3 × 10 <sup>11</sup>	1.3 ± 0.5 × 10 <sup>11</sup>

5 <sup>a</sup> Data from Dominique (2006)

<sup>b</sup> Estimation based on the measurement of DW accumulated on a nylon rope staying 8 months in the river at the *Passerelle* station.

<sup>c</sup> from ICP-AES analysis.

10 <sup>d</sup> % of the relative abundance by atoms or by weight % (in brackets) determined by XPS (n=2). See Table SI-1 for raw data.

## Figure legends:

Figure 1. Map showing the location of the Petit-Saut dam and the stations *Passerelle*,  
5 *Vénus* and *Estuary* (indicated as a white star) along the Sinnamary Estuary in French  
Guiana. The semi-circle indicates the location of the dam.

Figure 2. Pictures of the ferruginous biofilms at the *Passerelle* (a, c, d, e, f) or at the  
*Vénus* stations (b). Photography of the biofilms recovering a tube (5 cm in diameter)  
10 or leaflets as substrata at *Passerelle* and *Vénus* stations, respectively. Optical  
microscopy picture showing bacterial microcolonies (mc) embedded in organic or Fe-  
bearing gel like matrix, organic matter appears in blue due to the Azur blue coloration  
(c). Transmission electron microscopy showing close interaction between bacteria  
and ferruginous material (d), a crumpled paper like Fe-phase (the inset image  
15 represents a selected area electron diffraction pattern revealing the solids as  
lepidocrocite) (e), and a non-diffracting granular Fe-phase (f).

Figure 3. a) X-ray diffractogram (Co,  $\lambda = 0.17902$  nm) and b) Raman spectra of the  
lyophilized ferruginous biofilm (a), chemically synthesized ferrihydrite-2-lines (b) and  
20 lepidocrocite (c) as references. Si means  $\text{SiO}_2$ , L means lepidocrocite and F means  
ferrihydrite.

Figure 4. Reduction course of the iron oxide constituting the lyophilized biofilm and  
inoculated with *Shewanella putrefaciens* cells. The total  $\text{Fe}^{\text{II}}$  consist in both  $\text{Fe}^{2+}$  in the  
25 soluble and solid phases. The anaerobic incubation of the lyophilized biofilm ( $25 \text{ g l}^{-1}$ )

was done with 70 mmol l<sup>-1</sup> of formate as the electron donor and with *S. putrefaciens* cells in duplicate at 8.4×10<sup>8</sup> (open triangle) or 3.2×10<sup>9</sup> (close triangle) cells ml<sup>-1</sup>. No cell was added in the control (open circle).

30 Figure 5. X-ray diffractograms (Co, λ = 0.17902 nm) of the lyophilized biofilm incubated with a resting cell suspension of *Shewanella putrefaciens* (LC, 8.4×10<sup>8</sup> cells ml<sup>-1</sup> and HC, 3.2×10<sup>9</sup> cells ml<sup>-1</sup>) or without *Shewanella* (control). All analysis were made after 70 d of incubation time, an additional analysis was made at 800 d with 3.2×10<sup>9</sup> cells ml<sup>-1</sup>. GR1 means green rust 1; M, means magnetite and CMC  
35 means Calcium Magnesium Iron Carbonate.

Figure 6. TEM micrograph (a) and SEM micrograph (b) of GR crystals from incubation of the lyophilized biofilm with *S. putrefaciens* (70 d of incubation time); optical and TEM pictures from incubation of synthetic γ-FeOOH with aliquot from  
40 *Estuary* surface sediment (180 d of incubation time) indicating a GR like crystals (arrow) within an aggregate of iron oxides (c) and a GR crystal with its electron diffraction pattern (d); TEM and optical pictures from incubation of fresh biofilms supplemented with electron donor showing solid diffracting as an hexagonal symmetry and GR like particles (arrow) (180 d of incubation time) (e, f).

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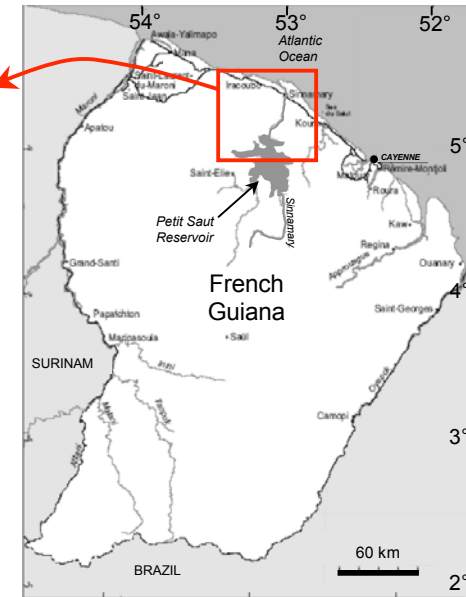
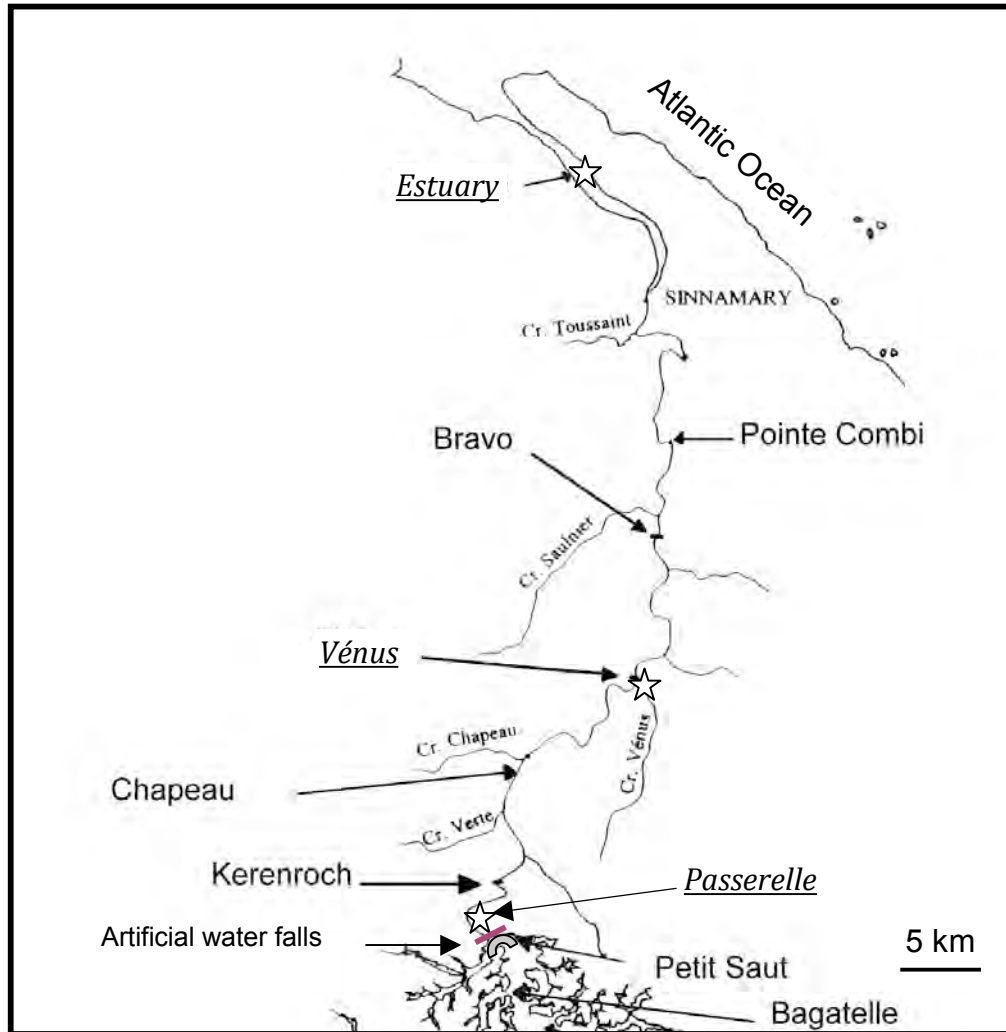
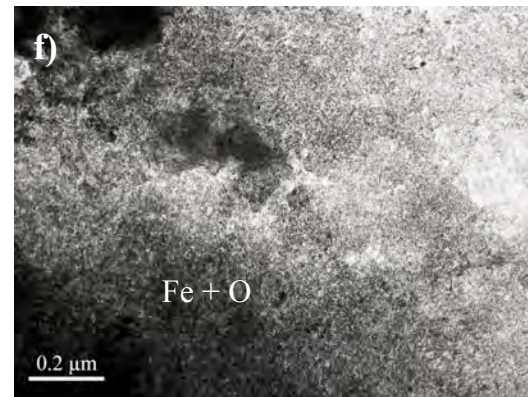
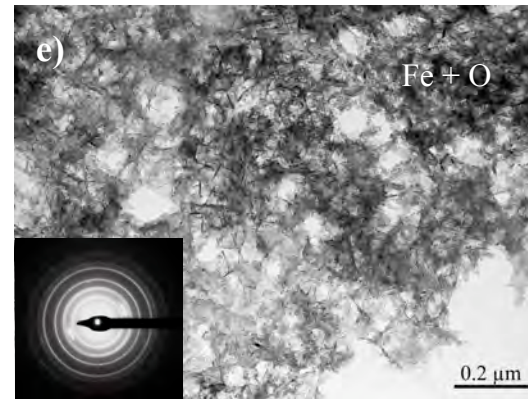
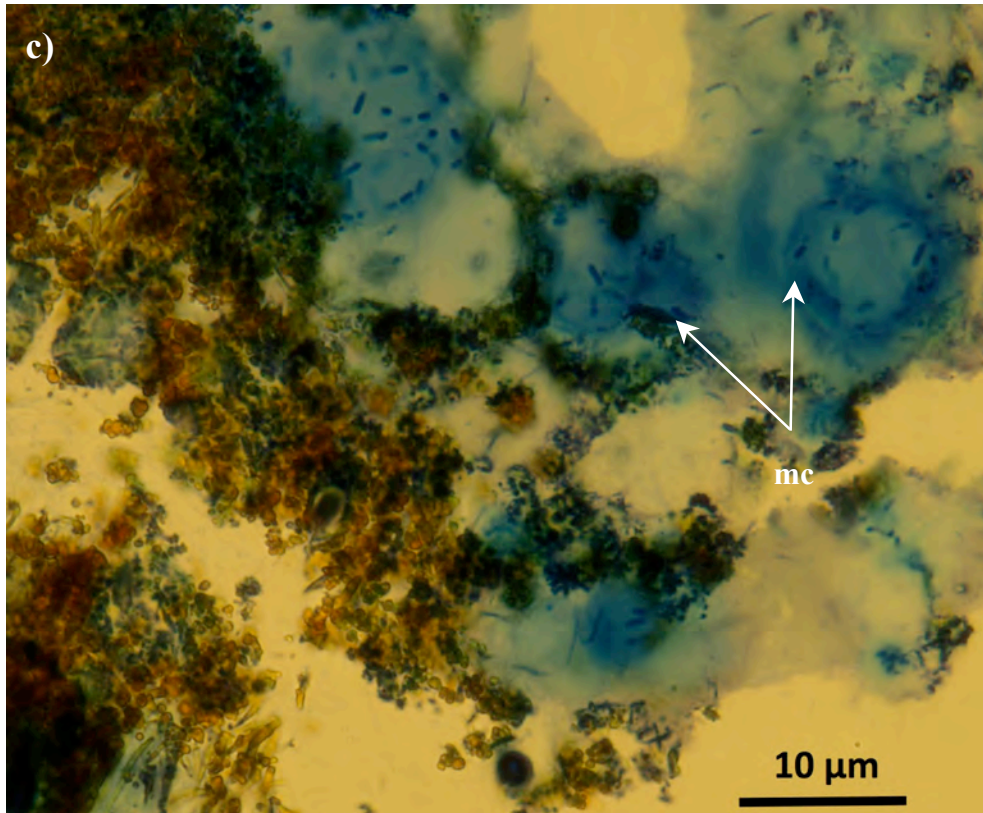
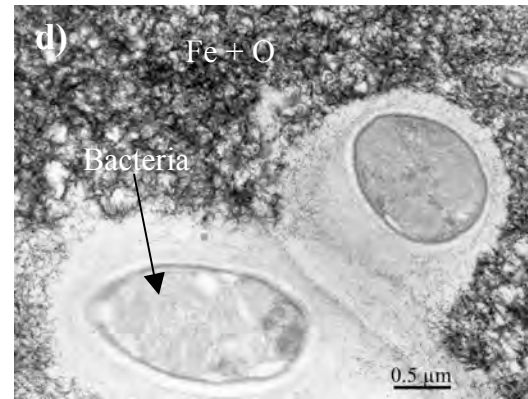
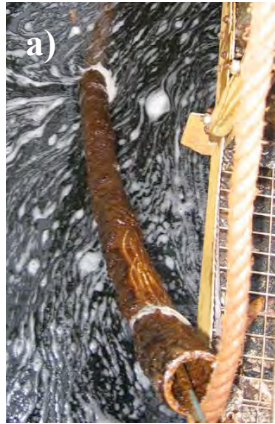
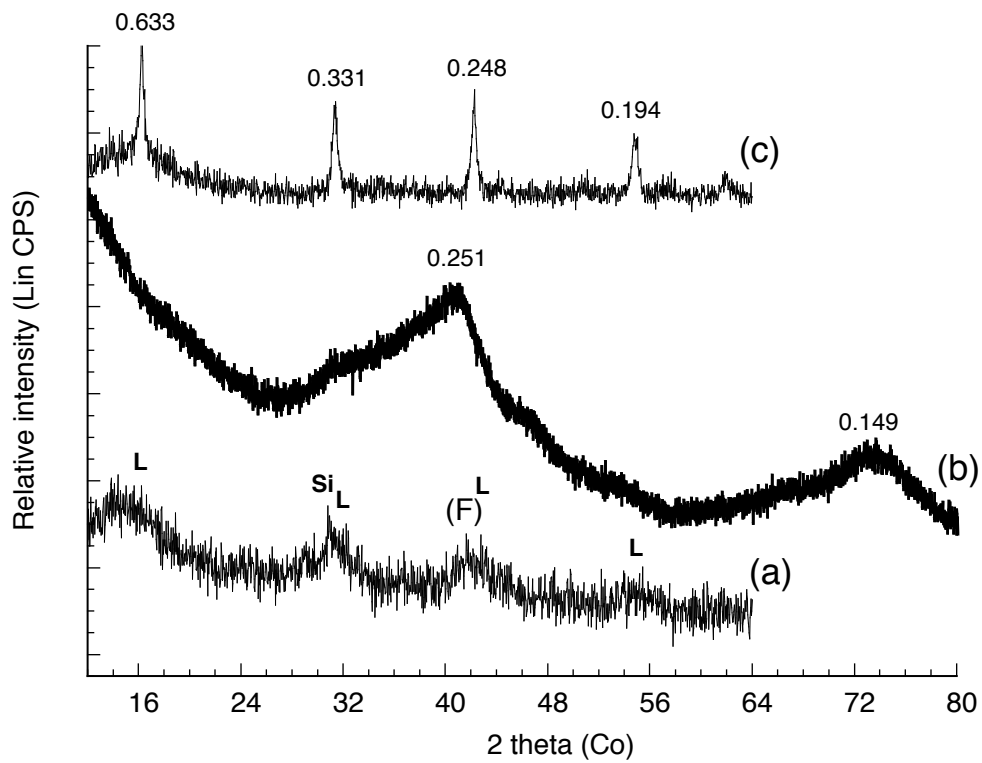
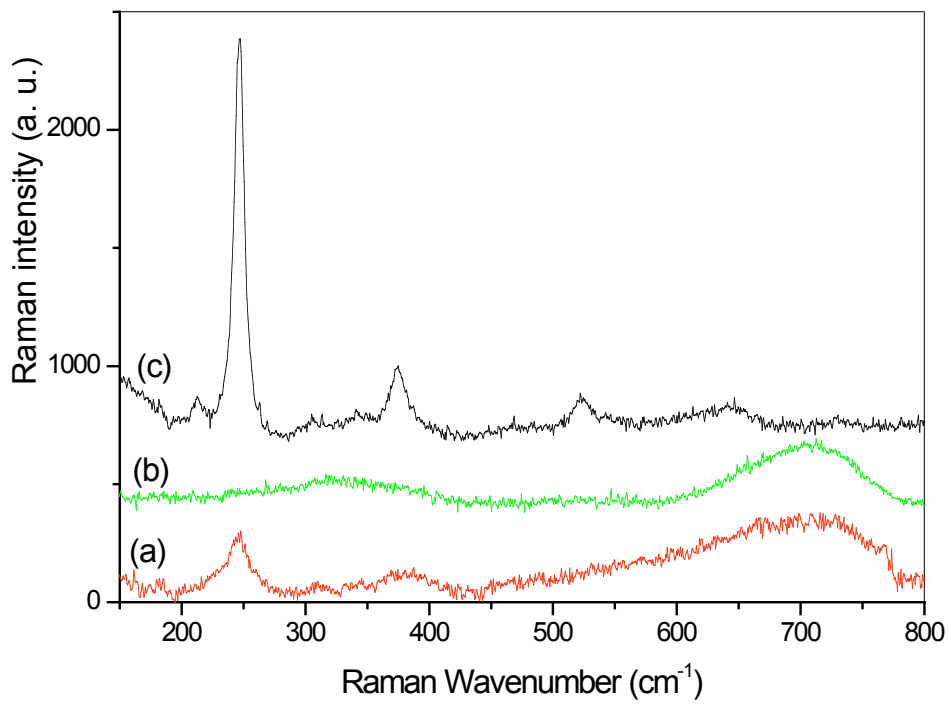


Figure 2





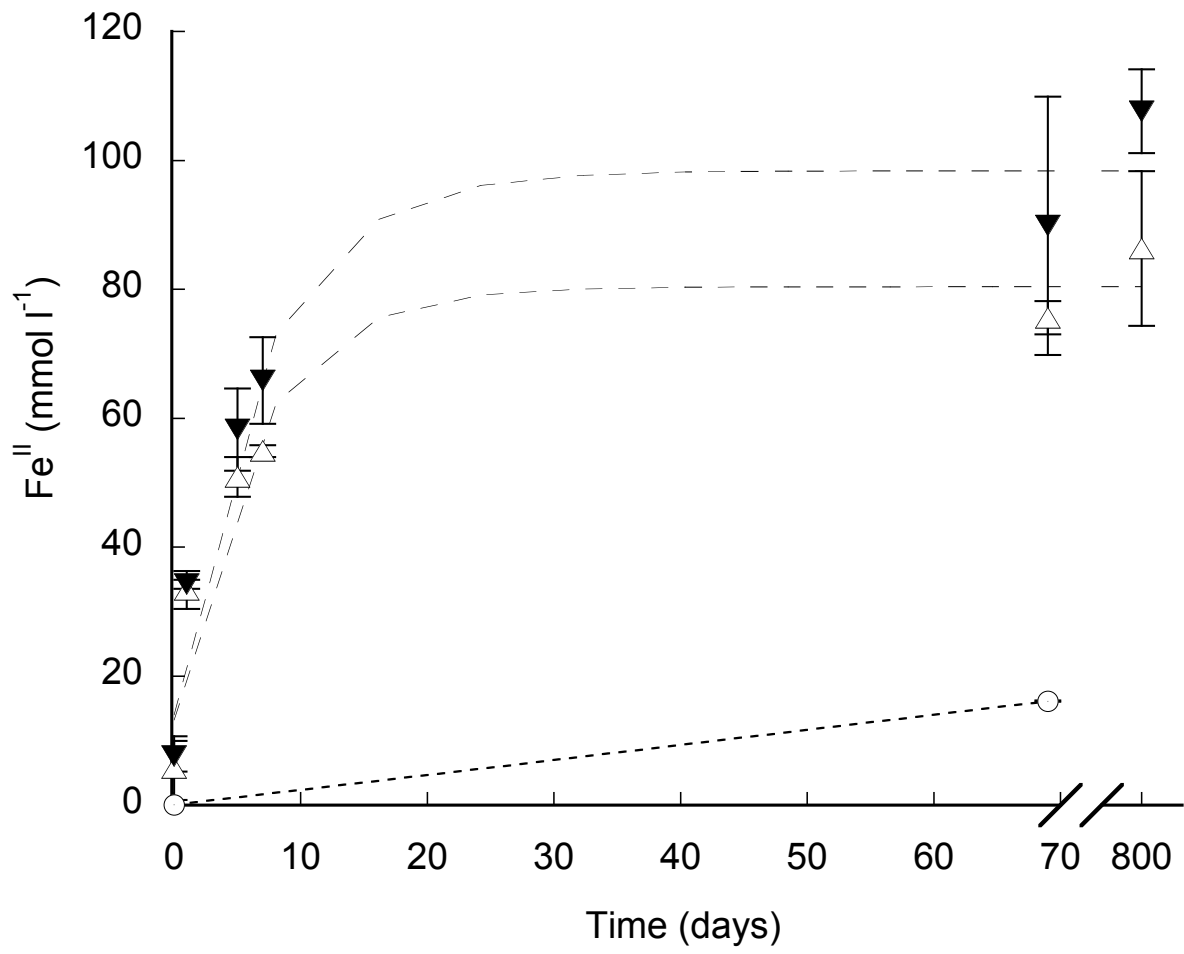
a)



b)

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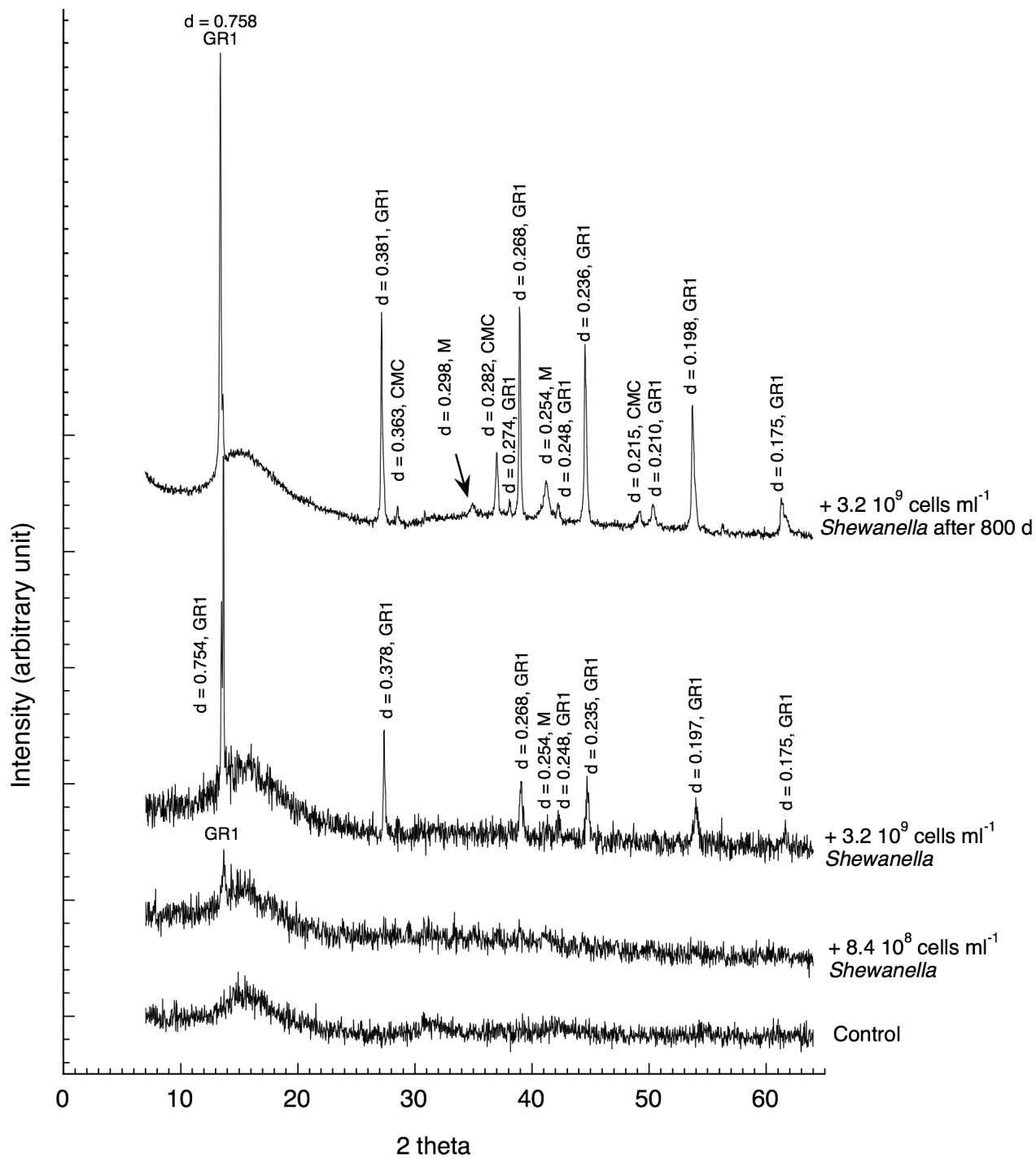
Figure 3.



5

Figure 4.

Fig. 5



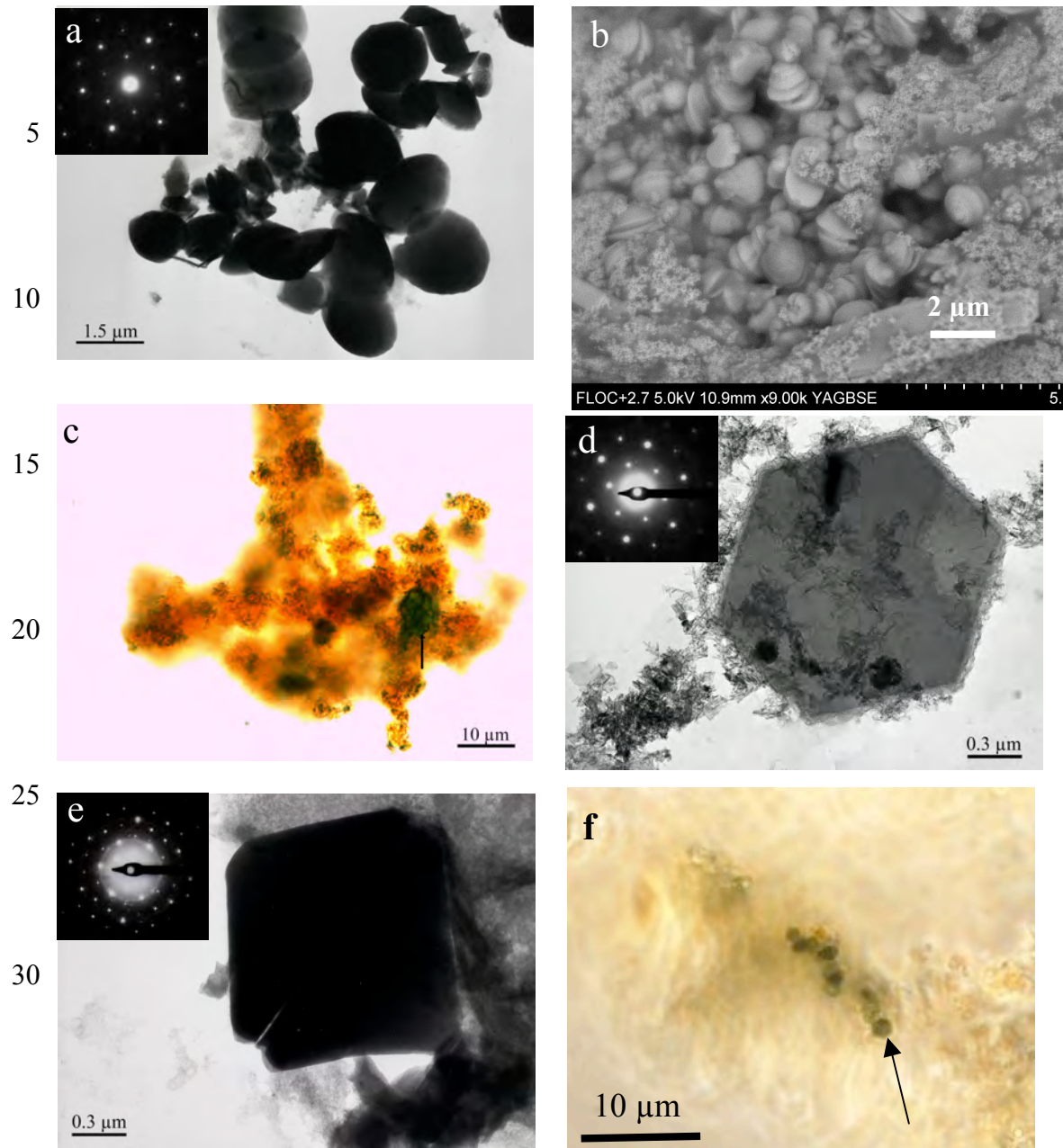


Figure 6.

## Supporting information

### The formation of green rust induced by tropical river biofilm components

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**Table SI-1. Quantification report from XPS analysis**

Peak	Position BE (eV)	FWHM (eV)	Raw area (cps)	RSF	Atomic conc %	Mass conc. %
Fe <sub>2p</sub>	710.788	3.777	14822.1	1.971	8.33	27.13
O <sub>1s</sub>	530.888	3.332	23741.1	0.780	35.00	32.65
N <sub>1s</sub>	399.588	2.147	1104.9	0.477	2.73	2.23
C <sub>1s</sub>	284.588	1.522	12348.2	0.278	53.76	37.66
S <sub>2p</sub>	162.988	2.016	91.7	0.668	0.18	0.33

10 **Table SI-2.  $d_{hkl}$  parameters of lepidocrocite from literature and from this study.**

$(hkl)$	$d_{hkl}$ (nm) from literature		$d_{hkl}$ (nm) from this study	
	Ref <sup>a</sup>	Ref <sup>b</sup>	By electronic diffraction (Fig. 2c)	By XRD (Fig. 3a)
(200)	0.626	0.634	-	0.620 – 0.765
(210)	0.329	0.333	0.331	0.322 – 0.332
(301)	0.247	0.250	0.244	0.243 – 0.256
(111)	0.238	0.236	0.237	0.233 – 0.241
(501)	0.193	0.196	0.195	0.192 – 0.197

<sup>a</sup> Cornell and Schwertmann (1996).

<sup>b</sup> Zegeye *et al.* (2007).

15

**Table SI-3. Mössbauer hyperfine parameters of spectra measured at room temperature of the lyophilized ferruginous biofilms.**

	$\delta$ (mm s <sup>-1</sup> )	$\Delta$ (mm s <sup>-1</sup> )	RA
D <sub>L</sub>	0.33	0.55	74 %
D <sub>F</sub>	0.34	0.91	26 %

$\delta$  = isomer shift taking  $\alpha$ -iron as reference at ambient;  $\Delta$ , quadrupole splitting; RA, relative abundance.

20 D<sub>L</sub> = doublet from lepidocrocite; D<sub>F</sub> = doublet from ferrihydrite.

**Table SI-4.**  $d_{hkl}$  parameters of GR1(CO<sub>3</sub><sup>2-</sup>) from literature and from this study.

$(hkl)$	$d_{hkl}$ (nm) from literature			$d_{hkl}$ (nm) from this study (Fig. 5)	
	Ref. <sup>a</sup>	Ref. <sup>b</sup>	Ref. <sup>c</sup>	Electronic diffraction	XRD
(003)	0.7530	0.751	0.755	-	0.752-0.764
(006)	0.3759	0.373	0.381	-	0.378-0.381
(101)	0.2720	0.273	0.274	-	0.274
(012)	0.2668	0.265	0.269 0.267 <sup>d</sup>	0.272	0.268
(015)	0.2344	0.233	-	-	0.235-0.236
(018)	0.1967	0.196	0.198	-	0.197-0.198
(0012)	0.1880	0.188	0.190	-	0.188-0.190
(1010)	0.1740	0.173	0.175	-	0.175
(120)	0.1550		0.156 <sup>d</sup>	0.158	-

<sup>a</sup> Hansen *et al.* (1989).<sup>b</sup> Drissi *et al.* (1995).<sup>c</sup> Jorand *et al.* (2007).<sup>d</sup> Data from electronic diffraction.**Table SI-5.** Mössbauer hyperfine parameters of spectra measured at room temperature after bioreduction of the lyophilised biofilm by *Shewanella putrefaciens*.

	$\delta$ (mm s <sup>-1</sup> )	$\Delta$ (mm s <sup>-1</sup> )	H (kOe)	RA
D <sub>1</sub> (Fe <sup>II</sup> <sub>GR</sub> )	1.21	1.99		35 %
D <sub>4</sub> (Fe <sup>III</sup> <sub>GR</sub> )	0.34	0.57		25 %
D <sub>3</sub> (Fe <sup>II</sup> <sub>CMC</sub> )	1.12	2.66		13 %
D <sub>2</sub> (Fe <sup>II</sup> <sub>L</sub> )	0.15	0.47		7 %
S <sub>1</sub> (magnetite)	0.28	0	483	6 %
S <sub>2</sub> (magnetite)	0.62	0	452	13 %

$\delta$  = isomer shift taking  $\alpha$ -iron as reference at ambient;  $\Delta$ , quadrupole splitting; RA, relative abundance; H; hyperfine field. GR = green rust, CMC = Calcium Magnesium Iron Carbonate.

## References

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Drissi H, Refait P, Abdelmoula M, Génin JMR (1995) The preparation and thermodynamic properties of Fe(II)-Fe(III) hydroxide-carbonate (Green Rust 1); Pourbaix diagram of iron in carbonate-containing aqueous media. *Corrosion Sciences* **37**, 2025–2041.

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## Supporting information

### The formation of green rust induced by tropical river biofilm components

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SI Figure Caption:

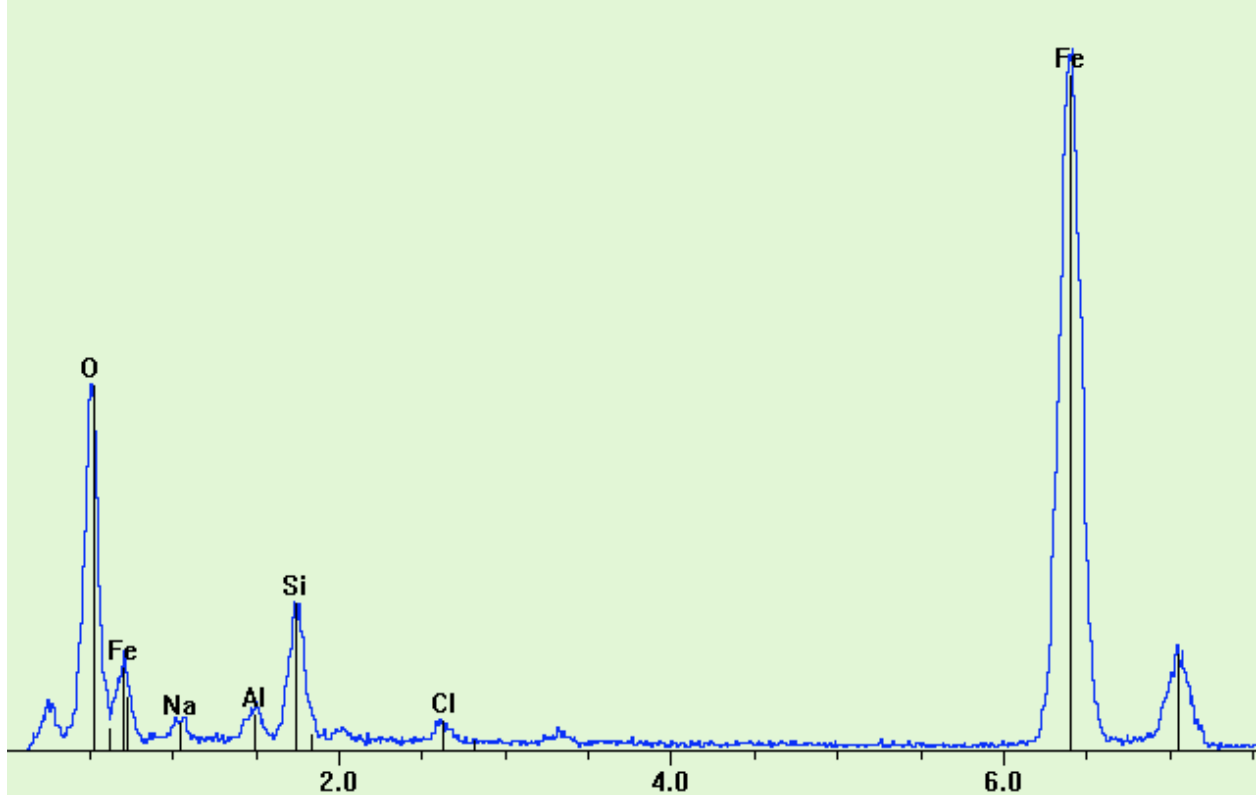
10 Fig. SI-1. EDX analysis of the second phase analyzed from the biofilm (from Fig. 2f).

Fig. SI-2. Mössbauer spectra measured at ambient temperature of the lyophilized biofilm. See Table SI-2 for indication.

15 Fig. SI-3. Mössbauer spectra measured at ambient temperature of the lyophilised biofilm after bioreduction by *Shewanella putrefaciens*. See Table SI-4 for indication.

20 Fig. SI-4. X-ray diffractogram (Co,  $\lambda = 0.17902$  nm) of the solids from incubation of synthetic  $\gamma$ -FeOOH with aliquot from *Estuary* surface sediment (~ 3 years of incubation time) indicating green rust (GR1) and vivianite (V).

Fig. SI-5. Images from fresh ferruginous biofilms (*Passerelle* site) showing elements (arrows) suggesting twisted like structure from *Gallionella* sp., by optical microscopy (a) and by scanning electronic microscopy (b).



Element	Line	keV	CL Ratio	Wt%	At%
O	KA1	0.523	2.3200	31.16	57.73
Na	KA1	1.041	1.7000	2.58	3.33
Cl	KA1	2.622	1.3000	1.25	1.05
Fe	KA1	6.403	1.4800	58.65	31.13
Si	KA1	1.740	1.0000	5.07	5.35
Al	KA1	1.487	1.0400	1.28	1.41
<b>Total</b>			<b>0.0000</b>	<b>100.00</b>	<b>100.00</b>

Fig. SI-1

Fig. SI-2

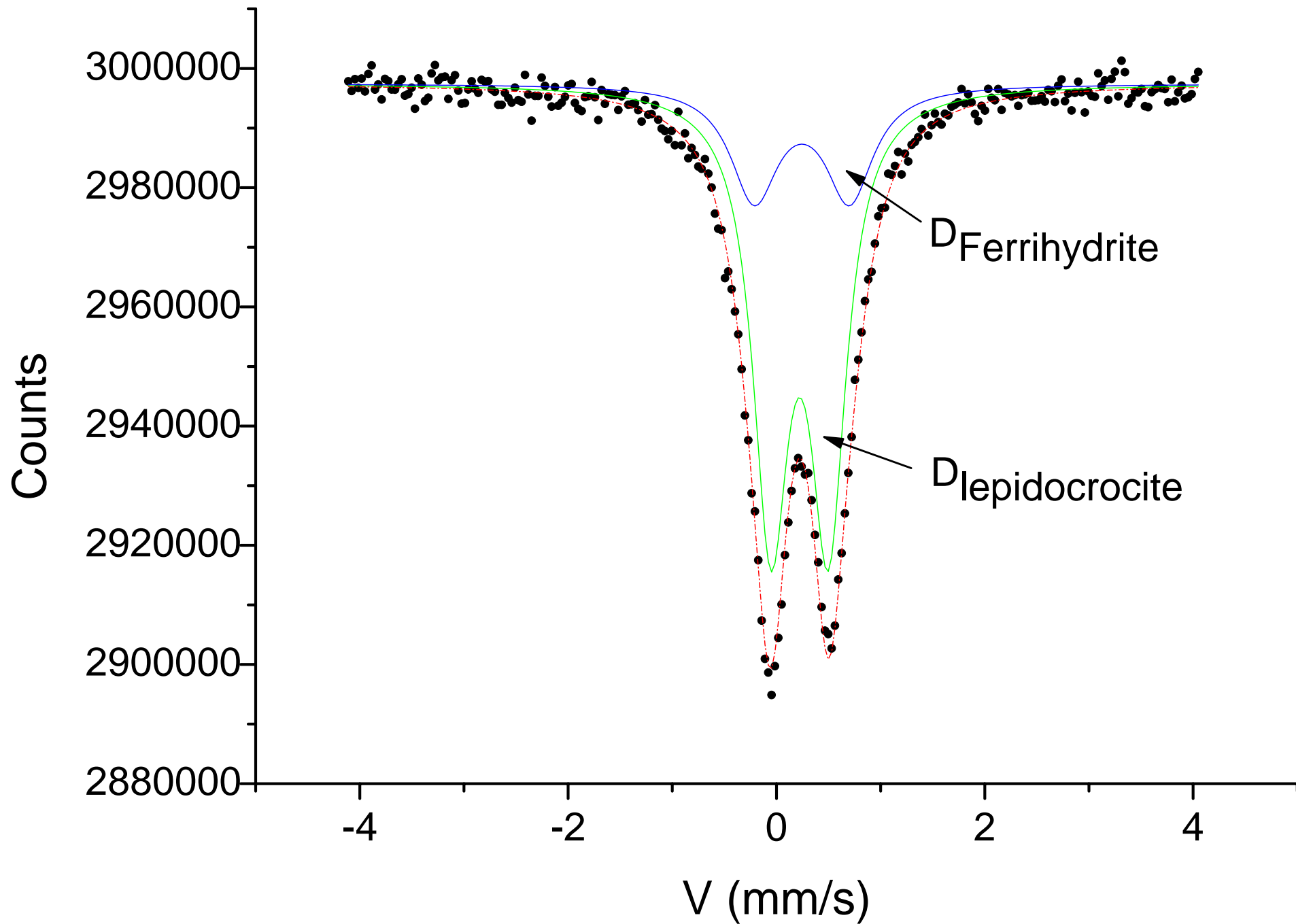
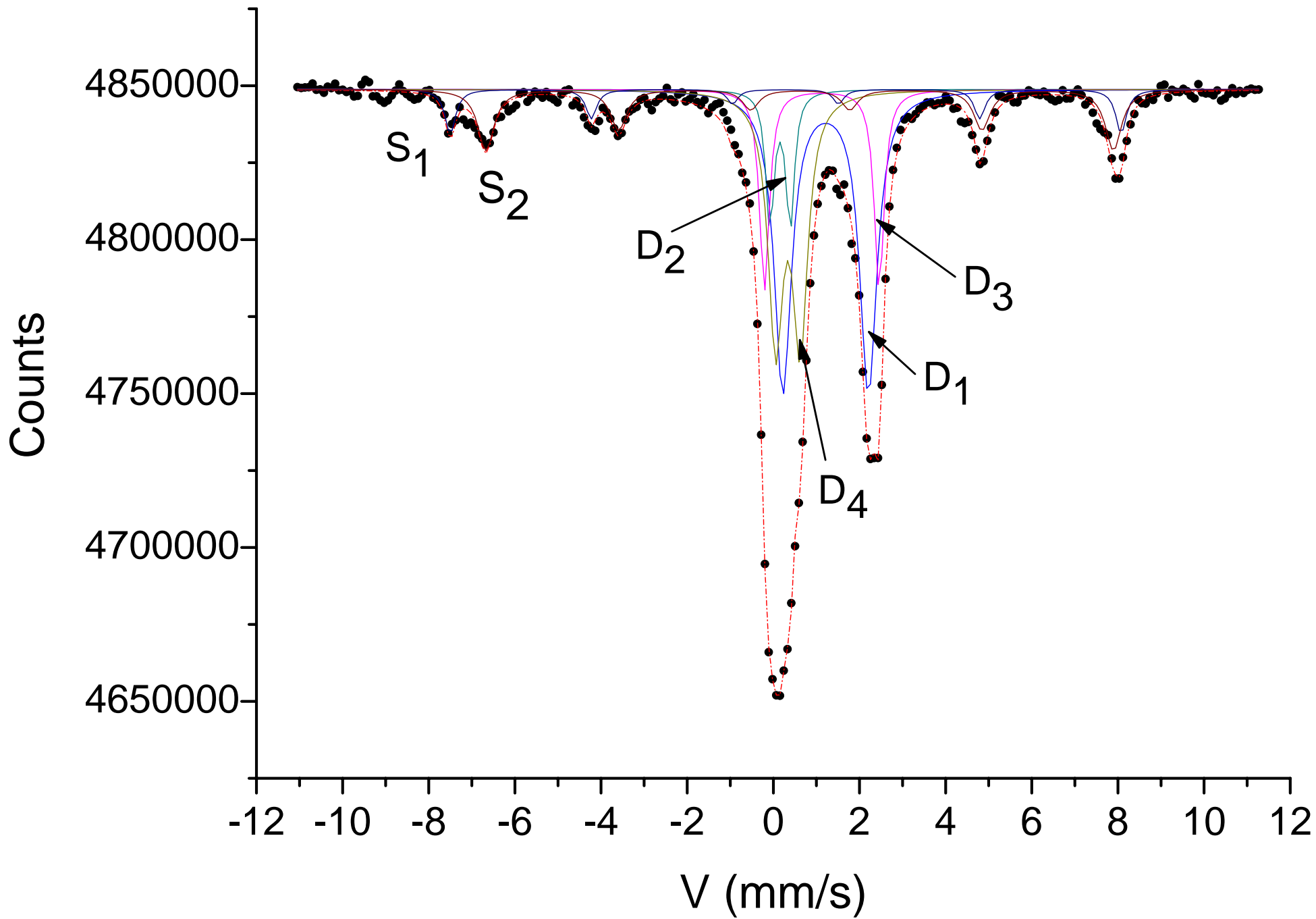


Fig. SI-3



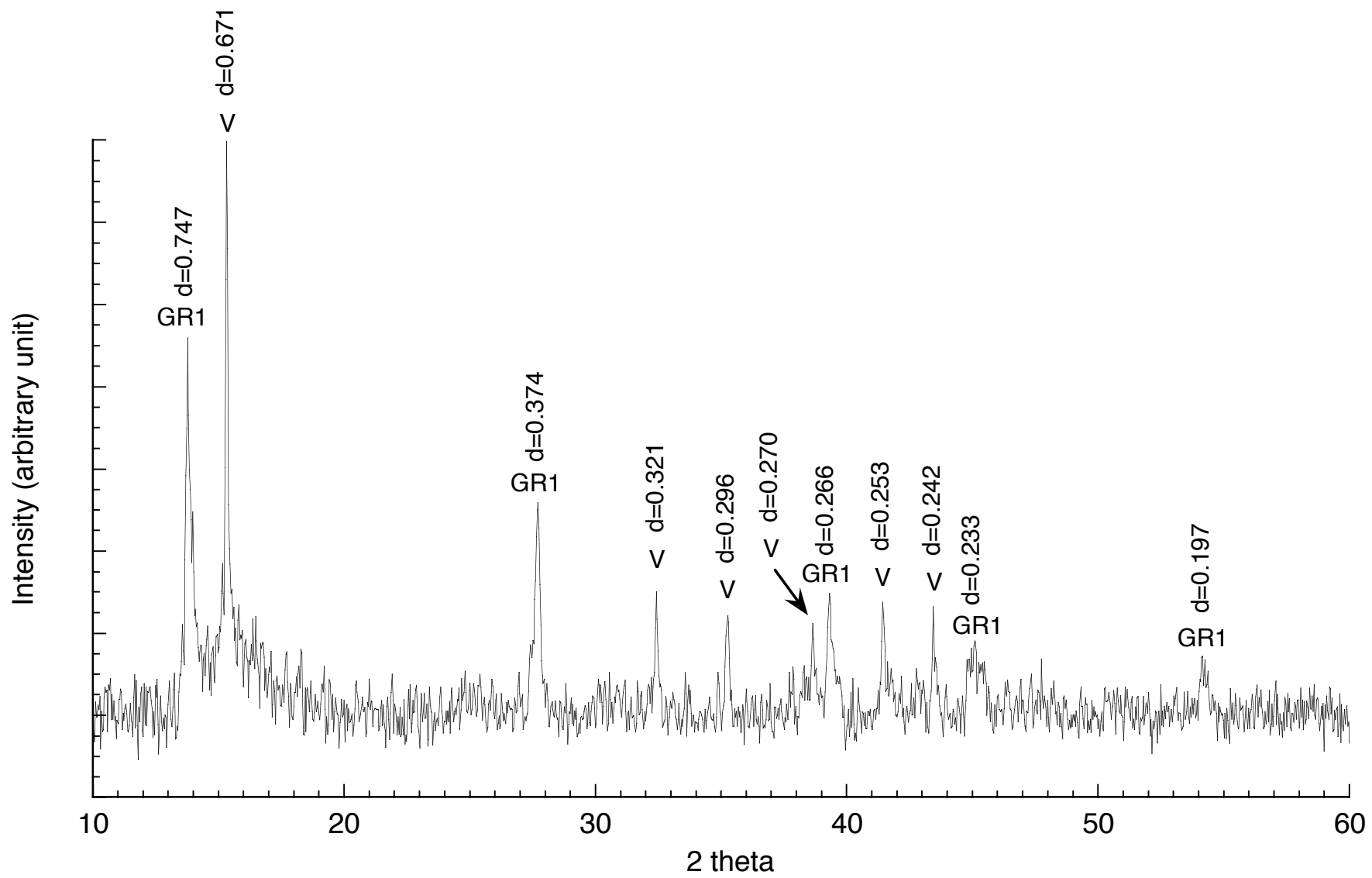
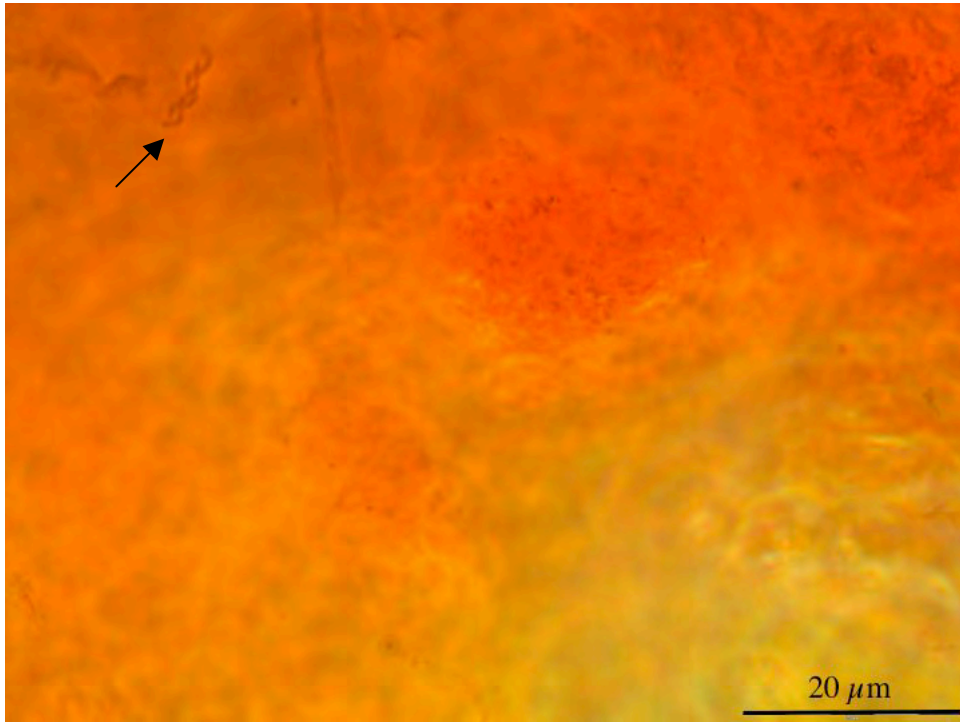


Figure SI-4



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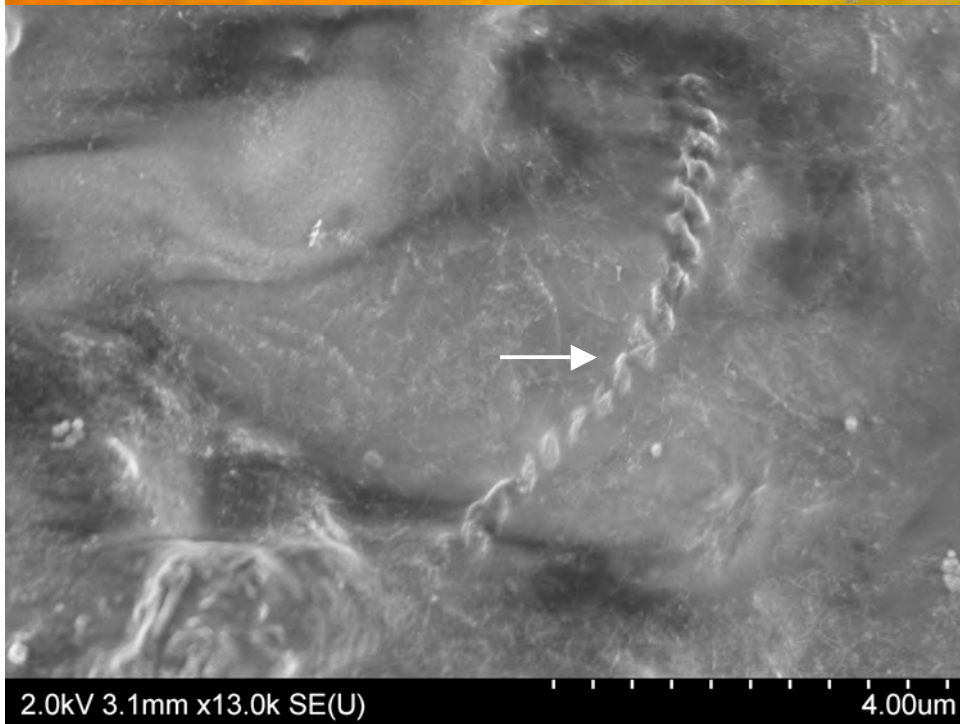


Fig. SI-5