Adsorption of zwitterionic fluoroquinolone antibacterials to goethite: A charge distribution-multisite complexation model

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ABSTRACT

Fluoroquinolone (FQ) antibacterials are aquatic contaminants of emerging concern (CEC), and adsorption to mineral surfaces is expected to play an important role in the fate, transport, and treatment of FQs. This study characterizes and models the adsorption of a zwitterionic FQ, ofloxacin (OFX), to goethite (α-FeOOH) over a wide range of pH (3–11), OFX concentration (20–500 μM), and electrolyte compositions (0.001–0.1 M NaCl and NaClO$_4$). Comparing OFX adsorption to structural analogues demonstrates that the carboxylate group is essential for binding to goethite. ATR-FTIR measurements indicate that FQs complex to goethite surfaces through carboxylate and carbonyl oxygen atoms, and that ClO$_4^-$ co-adsorbs with OFX. Adsorption of the zwitterionic OFX increases with increasing ionic strength and is enhanced in NaClO$_4$ relative to NaCl electrolyte, whereas adsorption of a non-zwitterionic analogue is insensitive to ionic strength. A CD-MUSIC (charge distribution-multisite complexation) model, incorporating multiple modes of surface complexation constrained by spectroscopic measurements and the crystallographic distribution of goethite surface sites, yields accurate predictions over wide-ranging solution conditions. According to the model, OFX adsorbs predominantly by inner-sphere complexation on terminal surfaces of the rod-shaped goethite crystals in NaCl electrolyte, and OFX-ClO$_4^-$ ion pairing in NaClO$_4$ induces formation of additional inner- and outer-sphere surface complexes on multiple crystal faces of goethite.

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1. Introduction

Adsorption of fluoroquinolone (FQ) antibacterial agents (Fig. 1) to charged mineral surfaces influences transport in soil and aquatic environments [1–5]. Previous studies have shown that FQs are strongly retained and persistent in the soils, in some cases persisting for several years after initial introduction through land application of sewage sludge [6]. In addition, FQ adsorption can significantly influence FQ bioavailability and control their rate of biodegradation [6]. FQ adsorption is also an important precondition for surface-mediated transformation processes, including oxidation by soil Fe and Mn oxides and photocatalytic transformation via semiconductor TiO$_2$ [4,7,8]. These reactions contribute to the deactivation of this pharmaceutically potent class of compounds [9,10].

The most commonly prescribed FQs are zwitterions at circumneutral pH conditions (Fig. 1), simultaneously possessing both an anionic carboxylate group and a cationic amine group, and this unique characteristic significantly influences adsorption behavior [1,3,11]. Previous reports have implicated one or the other charged moiety in controlling FQ binding with various mineral surfaces [3,4,7,8,12]. The carbonyl group on the quinoline ring has also been suggested to play a supporting role together with the adjacent carboxylate group in FQ binding to some surfaces [3,12]. Investigations of FQ complexation with divalent [13,14] and trivalent [15,16] metal ions in aqueous solutions support the involvement of both the carboxylate and carbonyl groups. Non-specific electrostatic binding through the protonated amine group controls FQ adsorption to minerals with high permanent negative charge (e.g., aluminosilicate clays) [1].

The current contribution is part of a broader effort to investigate the application of spectroscopically constrained charge distribution (CD) surface complexation models (SCM) [17] for predicting adsorption of zwitterionic FQ antibacterial agents to variably charged metal oxide surfaces. Incorporating the charge distribution in the adsorbing molecule allows for separate consideration of surface-bonding and non-bonding ionic functional groups at the aqueous-mineral interface. The objective of these studies is to challenge the SCMs and spectroscopic methods to provide
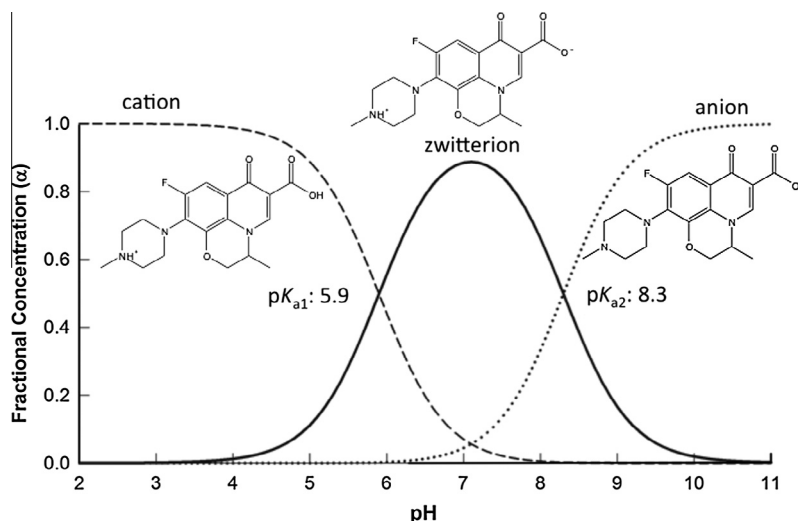
Fig. 1. Aqueous phase acid–base speciation of OFX, highlighting the predominance of the zwitterionic species at $pK_{a1} < pH < pK_{a2}$.

consistent data and predictions of the dominant modes of adsorption that give rise to the macroscopically observed FQ adsorption trends. In a previous contribution, zwitterionic FQ adsorption to nano-anatase (TiO_2) surfaces was well-predicted by a spectroscopically consistent CD-SCM involving inner-sphere, bidentate complexation of a deprotonated carboxylate group to Ti(IV) surface sites supported by hydrogen bonding of a neighboring carbonyl group to an adjacent protonated surface hydroxyl group [11]. Empirical data and corresponding CD-SCM also suggested that adsorption of zwitterionic FQs to positively charged surfaces can be enhanced through ion pairing of non-adsorbing protonated amine groups with certain electrolyte anions [11]. Photocatalytic oxidation studies further showed that rates of FQ oxidation were influenced by the speciation of adsorbed FQ molecules.

In this study, we extend the approach and modeling concept by investigating the adsorption of ofloxacin (OFX), a model zwitterionic FQ, to goethite (α-FeOOH), representative of abundant soil iron oxide minerals. Macroscopic OFX-goethite adsorption equilibria were measured over wide-ranging solution conditions, including varying pH, OFX concentration, and electrolyte composition. In addition, OFX adsorption was compared with structural analogues to evaluate the importance of individual ionic moieties (carboxylate, amine) on binding to goethite surfaces. In situ Fourier Transform infrared (FTIR) spectroscopy was used to identify probable modes of OFX surface complexation. Experimental data were then combined with goethite surface mineralogy information to develop a spectroscopically consistent surface complexation model to describe OFX adsorption to goethite particle surfaces over wide-ranging solution conditions. Whereas the CD model developed for OFX adsorption onto TiO_2 considered adsorption to a single site type on the dominant crystal face, for goethite we have extended the model formulation to include multisite surface complexation on multiple crystal faces of the goethite particles with binding site structures and densities set by crystallographic constraints (CD-MUSIC model [17]).

2. Materials and methods

2.1. Reagents and minerals

All reagents were used as received from the manufacturers without further purification. Ofloxacin (>99%), flumequine (>98%), 1-(2-fluorophenyl)piperazine (97%), NaCl (<99%) $NaClO_4$ (98%), NaOH (1.0 N reference standard), HNO_3 (1.018 N reference

standard), sodium 1-heptane sulfonate (SigmaUltra), and concentrated H_3PO_4 acid were purchased from Sigma Aldrich. Concentrated HCl and concentrated $HClO_4$ were obtained from Fisher Scientific. All solutions were prepared in deionized water (Barnstead Nanopure system; >18 MΩ cm resistivity). Ofloxacin methyl ester was synthesized as described in Supporting Information (SI) and purity was confirmed by ^1H NMR.

Details of goethite preparation have been reported elsewhere [18]. A working stock suspension of the mineral ($\sim$20 g/L) was prepared by dilution of the original goethite slurry ($\sim$200 g/L) and exact loading determined by gravimetric analysis. The goethite crystal structure was verified by X-ray Diffraction (XRD) analysis (data provided in SI). Specific surface area (64 m^2/g) was determined by 9-point N_2 Brunauer–Emmett–Teller (BET) analysis (Micromeritics, ASAP 2010) after freeze-drying and light grinding. Transmission electron microscopy (TEM) analysis (micrographs provided in SI) shows characteristic needle-shaped goethite crystals, 30–100 nm long and 8–15 nm wide.

2.2. FQ equilibrium adsorption measurements

Adsorption of OFX and structural analogues to goethite was measured in 200-mL batch suspensions containing 1–5 g/L goethite. Prior to adding the target FQ, mineral suspensions containing the desired electrolyte (NaCl or $NaClO_4$) and ionic strength (0.001–0.1 M) were continuously mixed and sparged overnight with hydrated CO_2-free $N_{2(g)}$ at pH $\sim$4 to exclude dissolved carbonate species. The suspensions were then adjusted to pH 11 (by NaOH) and OFX (20–500 μM) was introduced to initiate the adsorption experiments. The first adsorption sample (pH 11) was collected after mixing the OFX-goethite suspension for 5 min ($N_{2(g)}$ sparging continued throughout experiment). Subsequent samples were then collected from the suspension after acid (HCl or $HClO_4$) addition and pH equilibration at approximately 0.5 pH unit intervals. The process was continued until the suspension reached pH $\sim$3. Each pH-equilibrated sample aliquot was quickly sealed in a zero-head space centrifuge tube to prevent CO_2 gas-aqueous exchange. In general, the time to reach a stable pH reading after each acid addition was between 30 s and 2 min, but longer equilibration times were often necessary at circumneutral pH conditions. All pH-adjusted sample aliquots were centrifuged at the end of the experiment and the supernatants were collected for high performance liquid chromatography–photodiode array (HPLC–PDA) analysis to quantify FQ concentrations. The total experiment time needed to complete individual pH-edge experiments was approximately