Iron (III)-silica interactions in aqueous solution: Insights from X-ray absorption fine structure spectroscopy
Gs Pokrovski, J. Schott, F. Farges, Jl Hazemann

To cite this version:

HAL Id: hal-00693555
https://hal-upec-upem.archives-ouvertes.fr/hal-00693555
Submitted on 20 Feb 2013

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Iron (III)-silica interactions in aqueous solution: Insights from X-ray absorption fine structure spectroscopy

GLEN S. POKROVSKI1,* JACQUES SCHOTT2, FRANÇOIS FARGES3,4 and JEAN-LOUIS HAZEMANN5

1Institut des Sciences de la Terre d’Orléans (ISTO), CNRS (UMR 6113), 1A rue de la Férolellerie, 45071 Orléans cedex 2, France
2Géochimie: Transferts et Mécanismes, CNRS (UMR 5563)-OMP-Université Paul-Sabatier, 38 rue des Trente-six Ponts, 31400 Toulouse, France
3Laboratoire des Géomatériaux, Université de Marne la Vallée and FRE CNRS 2455, 77454 Marne la Vallée cedex 2, France
4Surface and Aqueous Geochemistry Group, Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA
5LGIT and Laboratoire de Cristallographie, CNRS, B.P. 166, 38042 Grenoble, France

(Received August 28, 2002; accepted in revised form February 17, 2003)

Abstract—The influence of aqueous silica on the hydrolysis of iron(III) nitrate and chloride salts in dilute aqueous solutions (mFe ~ 0.01 mol/kg) was studied at ambient temperature using X-ray absorption fine structure (XAFS) spectroscopy at the Fe K-edge. Results show that in Si-free iron nitrate and chloride solutions at acid pH (pH < 2.5), Fe is hexa-coordinated with 6 oxygens of H2O- and/or OH-groups in the first coordination sphere of the metal, at an Fe-O distance of 2.00 ± 0.01 Å. With increasing pH (2.7 < pH < 13), these groups are rapidly replaced by bridging hydroxyls (-OH-) or oxygens (-O-), and polymerized Fe hydroxide complexes form via Fe-(O/OH)-Fe bonds. In these polymers, the first atomic shell of iron represents a distorted octahedron with six O/OH groups and Fe-O distances ranging from 1.92 to 2.07 Å. The Fe octahedra are linked together by their edges (Fe-Fe distance 2.92–3.12 Å) and corners (Fe-Fe distance ~3.47 ± 0.03 Å). The Fe-Fe coordination numbers (Nedge = 1–2; Ncorner = 0.5–0.7) are consistent with the dominant presence of iron dimers, trimers and tetramers at pH 2.5 to 2.9, and of higher-polymerized species at pH > 3.

At pH > 2.5 in the presence of aqueous silica, important changes in Fe(III) hydrolysis are detected. In 0.05-m Si solutions (pH ~ 2.7–3.0), the corner linkages between Fe octahedra in the polymeric complexes disappear, and the Fe-Fe distances corresponding to the edge linkages slightly increase (Fe-Feedge ~ 3.12–3.14 Å). The presence of 1 to 2 silicons at 3.18 ± 0.03 Å is detected in the second atomic shell around iron. At basic pH (~12.7), similar structural changes are observed for the iron second shell. The Fe-Si and Fe-Fe distances and coordination numbers derived in this study are consistent with (1) Fe-Si complex stoichiometries Fe2Si1.2 and Fe5Si3.3 at pH < 3; (2) structures composed of Fe-Fe dimers and trimers sharing one or two edges of FeO6-octahedra; and (3) silicon tetrahedra linked to two neighboring Fe octahedra via corners. At higher Si concentration (0.16 m, polymerized silica solution) and pH ~ 3, the signal of the Fe second shell vanishes indicating the destruction of the Fe-Fe bonds and the formation of different Fe-Si linkages. Moreover, ~20 mol.% of Fe is found to be tetrahedrally coordinated with oxygens in the first coordination shell (RFe-O = 1.84 Å). This new finding implies that Fe may partially substitute for Si in the tetrahedral network of the silica polymers in Si-rich solutions.

The results of this study demonstrate that aqueous silica can significantly inhibit iron polymerization and solid-phase formation, and thus increase the stability and mobility of Fe(III) in natural waters. The silica “poisoning” of the free corner sites of iron-hydroxide colloids should reduce the adsorption and incorporation of trace elements by these colloids in Si-rich natural waters. Copyright © 2003 Elsevier Ltd

1. INTRODUCTION

The motivation of this study is the improved quantification of the interactions of iron with silica in aquatic surface environments. Such information is crucial to better understand the effect of aqueous silica on the geochemical cycle of iron and related trace elements. Iron (III) oxides and hydroxides play an important role in a variety of environmental and industrial processes, such as chemical weathering, soil formation, and water treatment for purification and consumer use. Colloidal and amorphous Fe(III) oxy-hydroxides are important adsorbents for many toxic organic and inorganic substances in natural waters, and thus they significantly influence the fate and toxicity of trace cations and anions in aquatic environments (e.g., Tessier et al., 1985; Manceau et al., 2000; Pokrovsky and Schott, 2002).

Silicic acid, Si(OH)4, is a major component of natural waters, attaining concentrations as high as 100 mg/L. There is ample evidence of silica-iron association in both surficial and hydrothermal processes. Important amounts of silica are incorporated into natural Fe-hydroxide precipitates such as ferrihydrite (Carlson and Schwertmann, 1981; Schwertmann and Taylor, 1989; Konhauser and Ferris, 1996). A strong chemical affinity between Fe(III) and Si is demonstrated by the formation, under both natural and laboratory conditions, of iron silicates like nontronite, ferric chlorites/serpentines and smectites (e.g., Decarreau et al., 1987; Bailey, 1988; Toth and Fritz, 1997; Drief et al., 2001, and references therein). The presence of silica in solution significantly influences Fe(III) hydrolysis and precipitation. For example, aqueous silica inhibits goethite
formation from solution and prevents colloidal Fe(III) hydroxides from coagulating (Schenk and Weber, 1968; Anderson and Benjamin, 1985; Vempati and Loeppert, 1989). The formation of ferryhydrite over lepidocrocite during oxidation of Fe(II) solutions is favored in the presence of silicic acid (e.g., Schwertmann and Thalmann, 1976; Mayer and Jarrel, 1996). Despite that several studies have been devoted to adsorption and incorporation of aqueous silica onto Fe(III) (oxy)hydroxides (McPhail et al., 1972; Sigg and Stumm, 1980; Hansen et al., 1994a, 1994b; Davis et al., 2002), little is known about the stoichiometry and stability of Fe-Si complexes in aqueous solution. Quantitative information about the stoichiometry and stability of Fe-Si complexes in aqueous solution is limited to FeSiOH$_3^{2+}$ that forms at acid pH between Fe$^{3+}$ and monomeric SiOH$_3^-$ (Weber and Stumm, 1965; Olson and O’Melia, 1973; Reardon, 1979). Structural aspects of the interactions between silicic acid and ferric iron hydroxide complexes during Fe(III) hydrolysis are, however, poorly known. The aim of the present work is to use X-ray Absorption Fine Structure (XAFS) measurements at the Fe K-edge to characterize the local environment around Fe in dilute aqueous solutions in the presence of dissolved silica over a wide range of pH.

In many studies dealing with iron hydrolysis in concentrated solutions (>0.1 m) and surface complexation of cations and anions with Fe(III) oxy-hydroxides and colloids (e.g., Combes et al., 1989, 1990; Waychunas et al., 1993; Bottero et al., 1994; Manceau and Charlet, 1994; Rose et al., 1997a; Manceau et al., 2000, and references therein), XAFS spectroscopy was the chosen method because it provides quantitative information at the atomic scale about the local structural environment of Fe and other elements in any system, including their aqueous and surface complexes (ligand’s identity and number, and interatomic distances). Until now, however, the exact structural position of silicon in Fe-dominated solids or solutions could not be detected by XAFS spectroscopy, because the weak signal from the light silicon backscatters at the Fe K-edge (∼7100 eV) is usually masked by the presence of heavier atoms (Fe) in concentrated iron solutions (e.g., Doelsh et al., 2000) or Si-bearing iron hydroxides (Manceau et al., 1995). Although limited information about the structural environment around silico- (and similar light elements like Al, P, e.g., Rose et al., 1997a; Idefonse et al., 1998; Gehlen et al., 2002) can be also obtained at the Si K-edge (∼1800 eV), the low energy provides a short spectral range, and usually requires high Si concentrations and heroic efforts to diminish the absorption by the sample environment. In contrast, currently available third-generation synchrotron radiation sources allow XAFS analyses in the fluorescence mode at iron K-edge at Fe concentrations as low as 10$^{-5}$ to 10$^{-3}$ m. Although such concentrations are higher than those usually encountered for Fe in natural waters, they are low enough to significantly slow down Fe(III) polymerization and precipitation, and to allow accurate characterization of Fe-Si interactions (complexation) which can be easily masked by Fe-Fe condensation and solid-phase formation at higher Fe concentrations. Therefore, it is expected that the XAFS results obtained in this study should help in the refinement of aqueous and surface complexation models of Fe(III)$_{aq}$/Fe hydroxides with silica and other trace oxy-anions which could be used for better understanding of the behavior of iron in natural waters and its role in the scavenging of inorganic and organic compounds.

2. MATERIAL AND METHODS

2.1. Sample Preparation

Iron(III)-bearing aqueous solutions for XAFS (X-ray Absorption Fine Structure) experiments were prepared by dissolving weighted amounts of hydrated ferric nitrate (Fe(NO$_3$)$_3$/H$_2$O, 99.9%, Aldrich Chemicals) or ferric chloride (~0.6-m FeCl$_3$ aqueous solution, Merck Chemicals) in doubly de-ionized water. The iron content of the initial solutions was checked by flame Atomic Absorption and was found to be close to the theoretical concentration within 2% of the total value. The pH of the solutions was adjusted by adding 1-nm nitric (HNO$_3$) or hydrochloric (HCl) acid, or 1-m tetramethylammonium hydroxide (N(CH$_3$)$_4$OH) Titrisol solutions; it was measured before and after each experiment with a combination pH glass electrode (SCHOTTL-H61) calibrated on the activity scale using the NIST tritarate, phthalate, phosphate and borate buffers (pH$_{H_2PO_4}$ = 1.69, 4.00, 6.87 and 9.21, respectively) and 0.1-m HCl and 0.01-m NaOH solutions (pH$_{H_2PO_4}$ = 1.11 and 12.12, respectively). Silicic acid (H$_4$SiO$_4$) was introduced into the Fe-bearing solutions as weighted amounts of a 0.67-m Si solution, prepared by equilibration of amorphous silica powder (SiO$_2$.2H$_2$O) at ambient temperature in a 0.5-m tetramethylammonium hydroxide solution. Tetramethylammonium was chosen in this study as the major cation, because of its extremely low complexing affinity for metals in aqueous solution (Wesolowski et al., 1995) even in comparison to other commonly used background cations (Na$^+$, K$^+$). The influence of (CH$_3$)$_4$N$^+$ on Fe hydrolysis and Fe-Si complexing in solution can thus be neglected when analyzing XAFS spectra. To avoid possible polymerization and/or precipitation during sample preparation, solutions were vigorously stirred using a magnetic stirrer during mixing and pH adjustment, and then immediately filtered through a 0.2-μm Millipore filter. This procedure was expected to eliminate possible heterogeneous nucleation sites and, thus, to delay significantly colloidal and solid-phase formation (see below). Measurements were started within 1 h, and completed usually within 5 h after solution preparation. Iron and silica concentrations in the experimental solutions used for XAFS experiments were 0.01 and 0.05 m, respectively (with exception of a single FeCl$_3$ solution containing 0.16 m silica). Such high silica concentrations were chosen to allow unambiguous detection of the light silicon backscatters (see below). The pH of most solutions ranged from 1 to 3, which corresponds to H/Fe and OH/Fe hydrolysis total molar ratios from ~10 to ~0.1, and from ~0.1 to ~4 (depending on Si concentration), respectively. At pH > 3 in both Si-free and Si-bearing solutions, rapid precipitation of Fe-hydroxide was observed; however, at strongly basic pH (pH = 12–13, OH/Fe > 5–10) this precipitate dissolved yielding a clear purple solution whose XAFS spectrum was also recorded (Tables 2–4). Monomeric silica, total Si and total Fe concentrations were determined using the molybdate blue colorimetric method (Koroleff, 1976), ICP-MS (Inductively Coupled Plasma Mass Spectrometry; see details in Pokrovski and Schott, 1998), and flame atomic absorption spectroscopy (Pokrovski et al., 2002a), respectively. Selected solutions before and after XAFS measurements were filtered through a 0.2-μm filter, diluted to 5 to 20 ppm of Fe and Si, and stabilized by 2 wt.% HNO$_3$ for analyses of total Fe and Si performed after the XAFS session. Monomeric silica was analyzed as a function of pH (2.0, 3.65 and 10.95) and time elapsed (from few minutes to 5 h) after preparation in 0.05-m Si solutions prepared exactly in the same manner as the experimental ones. Each of these solutions was diluted at constant pH to 7 to 10 ppm of Si with aqueous HNO$_3$ or N(CH$_3$)$_4$OH and analyzed for Si(OH)$_3^-$ with an Autoanalyser II Technicon colorimeter (molybdate blue method) from 2 min to 1 h after dilution. This procedure allows, even at alkaline pH where the kinetics of depolymerization is very fast, to measure only monomeric silicic acid (and, possibly, silicic acid dimers) present in the initial concentrated solution (Koroleff, 1976; Iler, 1979; Dietzel and Ussov, 1976; Ildefonse et al., 1995). Analyses performed on solutions before and after XAFS spectra acquisition showed no changes in total Si and Fe concentrations in the limit of the analytical uncertainties (±5% of total concentration).
Silicic acid remained essentially nonmoneric (~90% of total Si) in the alkaline solutions during experiments. This is in agreement with equilibrium calculations using the stabilities of silicate oligomers formed in basic solutions (Baes and Mesmer, 1976). In acid solutions, silica polymerization occurred within few minutes, and only 15 to 20% of total Si was found to be monomeric, depending on solution pH (2–3.65) and time (few minutes to 5 h). Nevertheless, the structural environment of Fe derived from the XAFS spectra was found to be insensitive to the degree of silica polymerization (see below). In a solution with the highest Si concentration (0.16 m) at pH 3, a silica gel was observed after measurements. No significant pH changes (±0.1–0.2 pH unit) were recorded after experiments for all solutions. Although the majority of solutions at pH > 2 were significantly supersaturated with respect to Fe oxy-hydroxides (α-FeOOH, amorphous Fe[OH]₃), the constancy of Fe and Si concentrations and pH, measured before and after experiments on solutions filtered through 0.2-μm membrane filters, indicates that no precipitation of Fe or Fe-Si solid phases occurred during measurements. However, the presence of nano-particles of such phases or colloids, which could have passed through the 0.2-μm filter, cannot be completely excluded on the bases of chemical analyses only. Nevertheless, XAFS analysis indicates that such particles were likely to be insignificant in our solutions. First, successive XAFS scans, recorded in this study during at least 3 to 5 h for all solutions, were very similar for each given sample and were without suspicious noise and flaws, thus demonstrating that the local atomic environment of Fe remains the same in the experimental solutions. Second, as it will be shown below (section 3), the number of Fe-Fe neighbors derived from the EXAFS spectra of acid solutions corresponded to the dominant presence of small Fe polymeric species, and was much lower than what would be expected for Fe-bearing solid/colloidal particles. This indicates that no significant solid-phase formation occurred over at least the time of measurements (~5 h).

### Table 1. Structural parameters of the Fe(III) atomic environment in iron-bearing solids derived in this study from fitting Fe K-edge EXAFS spectra, and comparison with X-ray diffraction (XRD) data.

<table>
<thead>
<tr>
<th>Compound, chemical formula</th>
<th>Atom</th>
<th>( R_{\text{EXAFS}} ) (Å)</th>
<th>( N_{\text{EXAFS}} )</th>
<th>( \sigma^2 ) (Å²)</th>
<th>Atom</th>
<th>( R_{\text{XRD}} ) (Å)</th>
<th>( N_{\text{XRD}} )</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (III) nitrate, Fe(NO₃)₃ · 9H₂O</td>
<td>O</td>
<td>2.00</td>
<td>5.5</td>
<td>0.003</td>
<td>O1</td>
<td>1.974</td>
<td>2</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>O2</td>
<td>1.986</td>
<td>4</td>
<td> </td>
<td>O2</td>
<td>1.959</td>
<td>1</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>O3</td>
<td>1.88</td>
<td>1.7</td>
<td>0.002</td>
<td>O3</td>
<td>2.009</td>
<td>2</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>2.95</td>
<td>2F</td>
<td>0.004</td>
<td>O4</td>
<td>2.24</td>
<td>2</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Si1 + Ca1</td>
<td>3.28</td>
<td>4F</td>
<td>0.007</td>
<td>Al1</td>
<td>2.99</td>
<td>2</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>Si2</td>
<td>3.46</td>
<td>2F</td>
<td>0.002</td>
<td>Si1</td>
<td>3.26–3.29</td>
<td>3</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>Ca2</td>
<td>3.74</td>
<td>3F</td>
<td>0.015</td>
<td>Ca1</td>
<td>3.29</td>
<td>1</td>
<td> </td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Si2</td>
<td>3.46</td>
<td>2</td>
<td> </td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ca2</td>
<td>3.84–3.86</td>
<td>3</td>
<td> </td>
</tr>
<tr>
<td>Goethite, α-FeOOH</td>
<td>O1</td>
<td>1.94</td>
<td>3.1</td>
<td>0.005</td>
<td>O1</td>
<td>1.953</td>
<td>3</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>O2</td>
<td>2.08</td>
<td>2.5</td>
<td>0.006</td>
<td>O2</td>
<td>2.09</td>
<td>3</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>Fe1</td>
<td>3.03</td>
<td>2F</td>
<td>0.005</td>
<td>Fe1</td>
<td>3.01</td>
<td>2</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Fe2</td>
<td>3.28</td>
<td>2F</td>
<td>0.006</td>
<td>Fe2</td>
<td>3.28</td>
<td>2</td>
<td> </td>
</tr>
<tr>
<td></td>
<td>Fe3</td>
<td>3.44</td>
<td>4F</td>
<td>0.008</td>
<td>Fe3</td>
<td>3.46</td>
<td>4</td>
<td> </td>
</tr>
<tr>
<td>γ-LiAlO₂ with 1 wt.% Fe³⁺</td>
<td>O</td>
<td>1.86</td>
<td>3.1</td>
<td>0.0005</td>
<td>O</td>
<td>1.82</td>
<td>4</td>
<td>WR</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>3.15</td>
<td>4.2</td>
<td>0.007</td>
<td>Al</td>
<td>3.12</td>
<td>4</td>
<td>M</td>
</tr>
<tr>
<td>Error of EXAFS fit</td>
<td>±0.01</td>
<td>±0.5</td>
<td>±30%</td>
<td> </td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* \( R = \) Fe-neighbor mean distance, \( N = \) Fe coordination number, \( \sigma^2 = \) squared Debye-Waller factor (relative to \( \sigma^2 = 0 \) adopted in the calculation of reference amplitude functions by FEFF, see text).

b References for XRD data: HB: Hair and Beattie (1977); D: Dollase (1971); S: Szytula et al. (1968); M: Marezio (1965), WR: Waychunas and Rossman (1983).

c \( f = \) parameter was fixed to crystallographic value during fit.

d \( parameters derived from EXAFS fitting.

### 2.2. XAFS Spectra Acquisition and Data Reduction

XAFS spectra (including the X-ray absorption near edge structure region or XANES, and the extended X-ray absorption fine structure region or EXAFS) were collected at ambient temperature (20 ± 1°C) in the fluorescence mode at the Fe K-edge (~7130 eV) over the energy range 7000 to 8000 eV on the collaborative research group IF BM32 beamline at the European Synchrotron Radiation Facility (ESRF, Grenoble, France). The storage ring was operated at 6 GeV with a 200–150 mA current. The beam energy was selected using a Si(111) double crystal monochromator with dynamical sagittal focussing. The fluorescence spectra were collected using a Canberra 30-element solid-state detector. The solutions were placed in a special Teflon cell with Kapton-film windows. The cell handling and spectra acquisition procedure were similar to those described in Pokrovski et al. (2000, 2002b). To obtain the necessary signal-to-noise ratio for quantifying next-nearest neighbors (Fe, Si) around the absorbing Fe atoms, three scans (of ~50 min/spectrum time) for each solution were collected to high energy values (up to \( \Delta E = 14–15 \) Å⁻¹, where \( \Delta E \) is the photo-electron momentum). After acquisition, all scans for each sample were carefully inspected for each individual solid-state detector and, if found reasonably free of beam intensity fluctuations and other flaws, were added together. Goethite, α-FeOOH, ferric iron nitrate, Fe(NO₃)₃ · 9H₂O, epidote, Ca₂(AlFe³⁺)(Si₂O₇)(SiO₄)(OH)₂, and LiAlO₂, doped with 1 wt.% of Fe³⁺, which can serve as model compounds for Fe local environment (see Wilke et al., 2001), were recorded in the transmission mode to exclude self-absorption effects.

Data analysis was performed with the XAFS 2.6 package (Winterer, 1997) using the “standard” procedure (Teo, 1986). Details about spectra reduction can be found in Pokrovski et al. (2002b). Briefly, the spectra before-edge spectral region (7000–7100 eV) was fitted using a straight line and subtracting this from the whole spectrum. Then, the spectra were normalized for atomic absorption, based on the average absorp-
results of the latter models were considered to be more reliable and they are reported in this study. Theoretical backscattering amplitude and phase-shift functions for Fe-O and Fe-Si, Fe-Fe, and Fe-Cl pairs were computed using the FEFF 8 ab initio code (Ankudinov et al., 1998), assuming the local structure around Fe in andradite garnet, Ca$_3$Fe$_2$Si$_2$O$_{12}$ (Hazen and Finger, 1989), α-FeOOH (Szytula et al., 1968), and FeOCI (Lind, 1970), respectively. The validity of the generated amplitude and phase functions was checked by fitting EXAFS spectra of Fe(III)-bearing solids. Interatomic distances and coordination numbers derived from fitting of model compounds are in close agreement with those obtained by X-ray Diffraction (XRD) in the limit of ±0.02 Å and ±0.5 atoms for first and next-nearest atomic shells (Table 1). The influence of anharmonic disorder in determining structural parameters was checked using the cumulant expansion method (Crozier et al., 1988; Farges, 1996; Farges et al., 1996; Soldo et al., 1998). The typical values of third- and fourth-order cumulants (C3 and C4) found when fitting the filtered signal for the Fe first coordination shell were of the order of 10$^{-4}$ and, consequently, too small to affect significantly R and N values derived from least-square fits without cumulants. As a result, to reduce the number of variables and thus the uncertainties on the derived parameters, we choose the harmonic approximation when extracting R, N and σ values for all Fe atomic shells. The influence of possible multiple scattering (MS) events within the Fe first and second coordination shells on the EXAFS spectra was also tested using the FEFF code, assuming local T$_4$ and O$_h$ geometries around Fe(III), as found in the model compounds investigated. However, we cannot exclude the possibility of unusual local geometries that can favor MS events. Nevertheless, with the exception of the most acid solutions (pH < 1), MS contributions were found to be negligible when fitting the next-nearest atomic shells.

3. RESULTS

3.1. XANES Analysis

3.1.1. Pre-Edge region

Normalized XANES spectra for selected Fe-bearing solutions and solids are presented in Figure 1. All spectra exhibit pre-edge features at 7112.5 ± 0.2 eV (Table 2, Figs. 1 and 2), which are caused by electronic transitions from the 1s to 3d
respectively, during solution preparation (see text for details).

Coordinated by six H that a similar geometry around the Fe(III) is octahedrally coordinated by six H₂O suggesting the same Fe octahedral coordination. In Si-free solutions of higher pH (pH > 2.5), the edge-crests are slightly shifted to lower energies (~7131.0 eV); the spectra’s shape is very similar to that of goethite (α-FeOOH) having a feature at ~7148 eV (identified by arrow B in Fig. 1). Because the goethite structure is characterized by distorted FeO₆ octahedra linked together by their edges and corners (Manceau and Combescot, 1988), similar structures could be expected in the iron oxy-hydroxide oligomer complexes formed at pH > 2.5 in solution. In the presence of 0.05-m Si at pH of ~2.8, the goethite features are partially suppressed, and the spectra shape more resembles those for acid solutions. These qualitative changes in the presence of silica at pH > 2.5 might indicate a more symmetrical Fe atomic environment in Fe-Si complexes like that at more acid pH. At higher silica concentration (0.16-m Si polymerized solution, pH = 3), the main-edge shape and position are significantly different from those for the 0.05-m Si solutions. The white-line position (~7130 eV) and the after edge-crest feature (at ~7138 eV, marked by arrow A in Fig. 1) are very close to those observed in the spectrum of Li(AlFe)O₂ (Fig. 1, Table 2). This similarity, together with the enhanced pre-edge feature (see

Table 2. Pre-edge and main-edge parameters from iron K-edge XANES spectra of Fe(III)-bearing solids and solutions measured in this study.

<table>
<thead>
<tr>
<th>Solids</th>
<th>Pre-edge</th>
<th>Main edge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Centroid position (eV)</td>
<td>Normalized height</td>
</tr>
<tr>
<td>Fe(NO₃)₃ · 9H₂O</td>
<td>7112.3</td>
<td>0.016</td>
</tr>
<tr>
<td>Goethite, α-FeOOH</td>
<td>7112.7</td>
<td>0.020</td>
</tr>
<tr>
<td>Epidote</td>
<td>7112.5</td>
<td>0.034</td>
</tr>
<tr>
<td>LiAlO₂ doped with 1 wt.% Fe³⁺</td>
<td>7112.5</td>
<td>0.174</td>
</tr>
<tr>
<td>Si-free solutions (0.01-m Fe³⁺)</td>
<td>7112.8</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>7112.8</td>
<td>0.020</td>
</tr>
<tr>
<td>Fe(NO₃)₃, pH 1.15, H/Fe = 10</td>
<td>7112.8</td>
<td>0.020</td>
</tr>
<tr>
<td>Fe(NO₃)₃, pH 2.36, OH/Fe = 0</td>
<td>7112.5</td>
<td>0.022</td>
</tr>
<tr>
<td>Fe(NO₃)₃, pH 2.80, OH/Fe = 2.8</td>
<td>7112.5</td>
<td>0.032</td>
</tr>
<tr>
<td>FeCl₃, pH 2.80, OH/Fe = 2.8</td>
<td>7112.5</td>
<td>0.032</td>
</tr>
<tr>
<td>Fe(NO₃)₃, pH 12.9, OH/Fe = 15</td>
<td>7112.5</td>
<td>0.026</td>
</tr>
<tr>
<td>Si-bearing solutions (0.01-m Fe³⁺)</td>
<td>7112.6</td>
<td>0.023</td>
</tr>
<tr>
<td>Fe(NO₃)₃, + 0.1-m HNO₃, pH 1.15, H/Fe = 10</td>
<td>7112.6</td>
<td>0.023</td>
</tr>
<tr>
<td>Fe(NO₃)₃, + 0.05-m Si, pH 2.10, OH/Fe = 0</td>
<td>7112.6</td>
<td>0.027</td>
</tr>
<tr>
<td>Fe(NO₃)₃, + 0.05-m Si, pH 2.80, OH/Fe = 2.0</td>
<td>7112.6</td>
<td>0.024</td>
</tr>
<tr>
<td>FeCl₃, + 0.05-m Si, pH 2.80, OH/Fe = 2.0</td>
<td>7112.6</td>
<td>0.068</td>
</tr>
<tr>
<td>FeCl₃, + 0.16-m Si, pH 2.95, OH/Fe = 4.0</td>
<td>7112.6</td>
<td>0.029</td>
</tr>
<tr>
<td>Fe(NO₃)₃, + 0.05-m Si, pH 12.5, OH/Fe = 10</td>
<td>7112.5</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Error of deconvolution ±0.2 eV ±10% ±15% ±0.3 eV ±0.5 eV

* H/Fe and OH/Fe stand for the molar ratio of iron salt concentration to the total added acid (HNO₃ or HCl) and base (N(CH₃)₂OH) concentration, respectively, during solution preparation (see text for details).

Spectra of 0.01-m Fe nitrate and chloride silica-free and silica-bearing acid solutions (pH < 2.5) are similar in shape and white-line positions (~7131.5 eV) to that of hydrated iron nitrate Fe(NO₃)₃·9H₂O suggesting the same Fe octahedral coordination. In Si-free solutions of higher pH (pH > 2.5), the edge-crests are slightly shifted to lower energies (~7131.0 eV); the spectra’s shape is very similar to that of goethite (α-FeOOH) having a feature at ~7148 eV (identified by arrow B in Fig. 1). Because the goethite structure is characterized by distorted FeO₆ octahedra linked together by their edges and corners (Manceau and Combescot, 1988), similar structures could be expected in the iron oxy-hydroxide oligomer complexes formed at pH > 2.5 in solution. In the presence of 0.05-m Si at pH of ~2.8, the goethite features are partially suppressed, and the spectra shape more resembles those for acid solutions. These qualitative changes in the presence of silica at pH > 2.5 might indicate a more symmetrical Fe atomic environment in Fe-Si complexes like that at more acid pH. At higher silica concentration (0.16-m Si polymerized solution, pH = 3), the main-edge shape and position are significantly different from those for the 0.05-m Si solutions. The white-line position (~7130 eV) and the after edge-crest feature (at ~7138 eV, marked by arrow A in Fig. 1) are very close to those observed in the spectrum of Li(AlFe)O₂ (Fig. 1, Table 2). This similarity, together with the enhanced pre-edge feature (see
section 3.1.1), suggests the presence in this solution of iron in tetrahedral coordination.

3.2. EXAFS Analysis of Silica-Free Solutions

3.2.1. First atomic shell

Normalized $k^3$-weighted EXAFS spectra and their Fourier Transforms (FT) of the studied Si-free solutions are presented in Figures 3a and 3b. In strongly acid chloride and nitrate solutions (pH < 2.4), both EXAFS and FT spectra exhibit a single contribution from a first shell of oxygens around Fe. Modeling this signal yields 6.0 ± 0.5 oxygens with a mean Fe-O distance of 2.00 ± 0.01 Å. This is in agreement with the EXAFS measurements of Combes et al. (1989) on highly concentrated Fe(III) hydrolyzed solutions ($m_{Fe} > 0.1$ m), and consistent with the predominance of Fe(H$_2$O)$_6^{3+}$ and Fe(H$_2$O)$_6$OH$_2^{3+}$ (Baes and Mesmer, 1976). Including chlorine in the fit of the first shell contribution of the 0.01-m FeCl$_3$ + 0.1-m HCl solution slightly improves the fit quality, suggesting the possible presence of ~0.3 ± 0.2 Cl atoms (Table 3). No Cl atoms were detected in the first Fe shell of FeCl$_3$ + HCl (0.01 < $m_{Cl}$ < 0.1) solutions at higher pH.

At pH from 2.4 to 2.8 in both nitrate and chloride solutions, the number of neighbors remains the same within errors as in the strongly acid solutions ($N_{Fe-O} = 5.5 ± 0.5$), but the average Fe-O distance decreases by 0.03 Å ($R_{Fe-O} = 1.97$ Å). The first coordination sphere of Fe deviates a little from a regular octahedron, as indicated by an increase of the DW factor (from 0.005 to ~0.01, see Table 3).

At basic pH, fits of the first Fe shell are consistent with two different Fe-O distances (1.92 and 2.05 Å), resembling closely the iron local environment in goethite (see Table 1). This is demonstrated in Figure 4. The EXAFS spectra of the first shell of both goethite and Fe basic solution are similar, but exhibit a distinct phase shift (indicated by the dashed line) in comparison to acid solutions.

3.2.2. Second and third atomic shells

At pH < 2, the minor feature observed at ~3.5 Å on the FT spectra (Fig. 3b, not corrected for phase shift) might correspond to both multiple scattering paths within the symmetrical FeO$_6$ octahedron and the second solvation shell around Fe$^{3+}$, by analogy with EXAFS and WAXS (wide-angle X-ray scattering) results on other trivalent cations like Cr$^{3+}$, In$^{3+}$, or Ga$^{3+}$ (Lindqvist-Reis et al., 1998). At pH from 2 to 2.4, this contribution is hardly discernable, probably due to the distortion of the octahedral symmetry of the first Fe shell. The small lobes
visible at the FT’s of these solutions above ~3 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, fully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.

At pH from 2.5 to 3, and from 12 to 13, the spectra exhibit an important second shell feature (Figs. 3a and 3b). This feature is, in part, similar to that of $\alpha$-FeOOH, and corresponds to several Fe-Fe pairs with distances ranging from 2.9 to 3.5 Å. The appearance of Fe-Fe contributions clearly demonstrates the formation of polymeric iron-hydroxide complexes. For an FeCl$_3$ solution at pH 2.8, the second shell feature was successfully fitted using two Fe-Fe subshells with distances of 3.04 and 3.46 Å (Table 4). For iron nitrate solutions at pH 2.8 and 12.7, the best fits were achieved with three Fe-Fe subshells, at 2.94, 3.46 Å are likely to be caused by the spectral noise. No second-shell iron atoms ($N_{fe-fe} < ~0.1$) could be detected in our dilute solutions at pH < 2.4.
3.3. EXAFS Analysis of Silica-Bearing Solutions

3.3.1. First atomic shell

In the presence of 0.05-m aqueous silica in strongly acid (pH < 2–2.5) and basic (pH > 12) solutions, no changes in the first coordination shell of iron were detected in comparison with their Si-free analogs (Table 3), which is also in agreement with the XANES analysis (see above). In contrast, in the intermediate pH region (2.7 < pH < 3), Fe-O₆ distances in 0.05-m Si chloride and nitrate solutions are distinctly longer than in their Si-free counterparts (2.00 instead of 1.97 Å, see Table 3 and Fig. 4) and close to those in more acidic solutions. This is also in line with the XANES analysis and can be interpreted by a partial destruction of the relatively short Fe-O-Fe linkages between FeO₆ octahedra and formation of longer Fe-OH or Fe-O-Si bonds.

In a more concentrated Si solution (0.16-m Si) at pH 3, the EXAFS spectrum is distinctly different, exhibiting important phase shifts and amplitude changes compared to the spectra of less concentrated Si solutions at similar pH (Figs. 4 and 5). Modeling of this spectrum is consistent with the presence of two distinct sets of Fe-O distances: ~1.84 Å (N = 1) and 1.99 Å (N = 4–5) (Table 3). The shorter Fe-O distance is very close to those found in tetrahedral sites of Fe⁺³ in Li[Al(Fe)O₂] (Table 1) and Fe(III)-bearing micas (e.g., Dyar et al., 2001; Giuli et al., 2001). The derived Fe-O distances and coordination numbers imply the presence of ~20% Fe in a tetrahedral coordination, probably substituting for Si in the tetrahedral framework of the silica polymers formed in this solution. Note that the percentage of [⁶²⁵]Fe deduced from the EXAFS analysis is in excellent agreement with that derived from the pre-edge data (see above).

3.3.2. Second and third atomic shells

In the spectra of acid solutions in the presence of 0.05-m Si (pH < 2.4), no second-shell Fe-Fe or Fe-Si contributions were detected in the limit of the spectral resolution (NFe-Fe < ~0.1; NFe-Si < ~0.5 atoms).

At pH 2.8 in contrast, important changes occur in the spectra of both 0.01-m ferric nitrate and chloride solutions in the presence of 0.05-m aqueous silica. This is manifested by the disappearance, in the total EXAFS spectrum, of the feature at ~7.5–8 Å⁻¹ which corresponded to the Fe-Fe contributions in Si-free solutions, and by distinct phase shifts in the region 7 to
9 Å⁻¹ (Fig. 5a). The contributions from the Fe-Fe edges at ~2.95 Å for nitrate solutions, and Fe-Fe double-corner linkages for both nitrate and chloride solutions, apparent in the RDF’s of the Si-free samples at these pH values, disappear in the presence of silica (Fig. 5b). The filtered second shell signal exhibits an important amplitude decrease and phase shift in the presence of silica (Fig. 6). These observations strongly suggest a destruction of the Fe-Fe linkages of iron hydroxide polymers, and the entering of Si in the second coordination shell of Fe. The analysis of the iron second shell for these samples was performed using either two Fe-Fe subshells or one Fe-Fe/Si subshell. Figure 7 shows such fits for Fe nitrate and chloride solutions at pH 2.8 with 0.05-m Si. It can be seen in this figure that the presence of iron atoms only cannot account for the observed second shell signal. Including light neighbors like oxygens or Cl/NO₃ do not affect the fit; adding a third Fe-Fe subshell resulted in less robust models, yielding highly correlated and unreasonable N and σ² values. In contrast, significant good-quality fits were obtained for both solutions using 0.9 to 1.3 Fe atoms at 3.12 ± 0.03 Å, and ~2 ± 0.5 Si atoms at 3.18 ± 0.03 Å (Fig. 7, Table 4). The uncertainties on these N and R values stem mostly from possible variations of the ΔEᵦ parameter (±2 eV, see section 2.2). Because Fe-Fe and Fe-Si individual electronic waves are shifted by > π/2 and thus are almost out of phase, the amplitude of the resulting spectrum for the second shell is quite sensitive to the value chosen for ΔEᵦ. Nevertheless, fits of the Fe-Fe/Si contributions at pH 2.8 were robust and always converged to the parameters reported in Table 4 whatever the starting values of R, N, and ΔEᵦ. These results confirm quantitatively the observations of RDF’s of these solutions, which indicate the destruction of Fe-Fe edge and double-corner bonds in the iron polymeric species in the presence of Si (Fig. 5b).

At pH 12.7 in the presence of 0.05-m Si, similar changes in the EXAFS spectrum were observed (Figs. 5 and 6). The suppression of Fe-Fe edge and corner contributions is apparent on the Fourier Transform (Fig. 5b). A fit of the second-shell signal confirms these observations, yielding two Fe-Fe edge
contributions at 2.93 and 3.11 Å (Table 4). The amplitude decrease of the second shell Fe-Fe signal was, however, much weaker than for less hydrolyzed solutions at acid pH (Fig. 6). Consequently, fits were less sensitive to the presence of silicon. It was found that addition of 2 ± 1 Si atoms at 3.17 Å improves only slightly the fit quality. This is in agreement with previous EXAFS studies of Fe hydroxide precipitates formed in the presence of Si (Doelsh et al., 2000), and hydrous iron silicate scale deposits (Manceau et al., 1995) that failed to detect the light Si in the second iron coordination shell dominated by Fe-Fe contributions. At earlier hydrolysis stages (pH < 3.0) of our experimental solutions of low Fe concentration, the Fe-Fe contributions to the EXAFS signal are significantly lower and thus allow accurate detection of light silicon atoms in the second shell.

With increasing Si concentration (0.16–m Si, pH = 3), Fe-Fe second shell contributions vanish indicating the almost complete destruction of iron polymers. The detection of Si was also impossible, probably because of an important disorder associated with various Fe-O-Si and Fe-O-Si contributions. More measurements in Si-rich solutions are required to distinguish between these different linkages.

4. DISCUSSION

4.1. Iron Hydrolysis and Polymerization in Dilute Solutions

The results of this study demonstrate that the Fe$^{3+}$ cation rapidly hydrolyses in dilute chloride and nitrate aqueous solutions via formation of Fe oxy-hydroxide polynuclear species composed of Fe(O/OH)$_n$ octahedra linked together by their edges and double corners. This is in good agreement with previous XAFS studies of Fe hydrolysis in concentrated solutions (>0.1-m Fe) that have shown the formation of large Fe polymers in chloride and nitrate solutions with increasing OH/Fe ratios or aging time (e.g., Combes et al., 1989, 1990; Bottero et al., 1994; Rose et al., 1997b). The number of edge (2.90–3.05 Å) and double-corner (3.40–3.50 Å) linkages derived in those studies increase, respectively, from 1 to 3.5 and from 1 to 2 in solutions with OH/Fe ratios > 1.5 (2 < pH < 5), suggesting the presence of large Fe oxy-hydroxide entities (e.g., “Fe$_{24}$”, Bottero et al., 1994). Such species are regarded as precursors for goethite, akaganite or hematite (depending on solution composition, temperature and time of aging). In the more dilute solutions of the present study, the number of edge-and corner-sharing neighbors at pH of ~2.8 is consistent with the formation of smaller Fe polymers, most likely a mixture of dimers, trimers and tetramers. At basic pH (OH/Fe > 5), the Fe-Fe coordination numbers ($N_{\text{edge}}$ = 2.0, $N_{\text{corner}}$ = 0.7; Table 4) correspond to tetrarners of and/or bigger polymeric species (e.g., “Fe$_{24}$”), in agreement with previous studies. The schematic structures of the main hydroxide polymers likely to form during Fe(III) hydrolysis are presented in Figure 8.

The results on Fe-hydrolysis obtained in this study can be compared with speciation calculations using the available stability constants for the iron dimer, Fe$_2$(OH)$_3$$^{4+}$, and trimer, Fe$_3$(OH)$_6$$^{5+}$, obtained from potentiometric measurements in dilute Fe nitrate or chloride solutions (e.g., Baes and Mesmer, 1976; Martell et al., 1998, and references therein). The distribution of Fe hydroxide species in a 0.01-m Fe(III) nitrate solution at 25°C and a 0.15-mol/L ionic strength is shown as a function of pH in Figure 9a. At pH < 2.4, calculations predict < 20% of total Fe is present as dimers, and < 5% as trimers, which corresponds to ~0.2 Fe atoms in the second Fe shell. This is close to the detection limit of Fe-Fe second neighbors of our EXAFS spectra. At higher pH (2.6 < pH < 3.0), calculations indicate that the dimer and trimer account for ~20 to 30% of total Fe each. This corresponds to $N_{\text{edge}}$ = ~0.4 to 0.5 and $N_{\text{corner}}$ = ~0.3 Fe atoms, assuming an edge-sharing dimer and a double-corner trimer (Bottero et al., 1994; Jolivet et al., 1994). Our EXAFS analysis yields significantly higher coordination numbers at these pH values, confirming the formation of bigger Fe polymers, likely tetramers (Fig. 8). Note that tetrameric species with edge and double-corner linkages were shown to form during Cr$^{3+}$ and Ga$^{3+}$ hydrolysis; they are also considered as precursors for the nucleation of Al and Fe(III) oxy-hydroxide phases (Jolivet et al., 1994, and references therein; Michot et al., 2000). The very high lability of Fe$^{3+}$ in comparison to Al$^{3+}$ or Cr$^{3+}$ makes it difficult to stabilize small Fe polymers in supersaturated solution in the absence of strongly complexing ligands (Jolivet et al., 1994) which can explain the absence of thermodynamic data for Fe-tetramers.
Consequently, the equilibrium calculations presented here give a simplified image of iron speciation especially at pH \( 3-4 \), which is likely dominated by tetrameric and/or bigger species.

### 4.2. Iron-Chloride Complexing

The presence of chlorine neighbors was not detected in the first and second Fe atomic shell in hydrolyzed 0.01-m FeCl\(_3\) solution at pH 2.8. This is in agreement with equilibrium calculations carried out using the available stability constants for Fe(III) chloride species (taken from the compilation of Tagirov et al., 2000), suggesting that only 6% of total Fe should be complexed in the form of FeCl\(_2^−/H\) and FeCl\(_2^+/H\) species in this solution. In strongly acid non-hydrolyzed solution (pH \( < 1 \), 0.1-m Cl\(^−\), 0.01-m FeCl\(_3\)), less than 0.3 Cl atoms could be detected in the Fe first shell from analysis of its EXAFS spectrum. Speciation calculations for this solution composition indicate that FeCl\(_2^+/H\) and FeCl\(_3^−\) represent respectively \( \sim 40 \) and \( \sim 10\% \) of total Fe. This corresponds to an average Fe-Cl coordination number of 0.6, if one assumes inner-sphere complexation. The lower first shell coordination number obtained in this study (\( N_{Fe-Cl} \sim 0.3 \), Table 3) suggests a portion of Fe-Cl species may be in the form of outer-sphere complexes which could not be detected by EXAFS analysis in this study. Thus, the presence of Cl atoms weakly bonded to Fe hydroxide species in outer coordination shells during iron hydrolysis cannot be completely excluded. More ordered second shell Fe-Fe structures observed in this study at pH 2.8 for 0.01-m chloride (two Fe-Fe subshells) compared to nitrate (three Fe-Fe subshells) solutions, imply that chloride can probably intervene in Fe hydrolysis in dilute solutions, as it was suggested for Cl-rich solutions (0.2–1.0-m Cl; Combes et al., 1989; Doelsch et al., 2000). However, the structural role of Cl\(^−\) during the hydrolysis of dilute Fe(III)-chloride solutions remains unclear. At ambient temperature, the negatively charged Cl\(^−\) could weakly interact with the outer shells of positively charged Fe polymeric oxy-hydroxide species and affect polymerization/nucleation kinetics. However, as it is demonstrated in this study, the role of Cl\(^−\) in Fe hydrolysis in dilute solutions is negligible as compared to that of silica.

### 4.3. Structure and Stoichiometry of Fe-Si Aqueous Complexes

XAFS measurements reported in this study unambiguously demonstrate that aqueous silica inhibits Fe\(^{3+}\) hydrolysis via formation of stable complexes with polymeric ferric oxy-hydroxide species. Fe-Si and Fe-Fe distances and coordination

---

1 The value of the first-order rate coefficient for the exchange of water molecules from the bulk solution into the inner coordination sphere of the hexacoordinated aquo ion is \( 1.6 \times 10^7 \), 1.3 and \( 2.4 \times 10^{-6} \) s\(^{-1}\) for Fe\(^{3+}\), Al\(^{3+}\) and Cr\(^{3+}\), respectively (Merbach and Akitt, 1990).
numbers derived in this study indicate that SiO$_4$-$\text{tetrahedra}$ substitute for double-corner FeO$_6$-$\text{octahedra}$ in the Fe(III)-polymers. The iron-silicon distance of 3.18 Å found in both nitrate and chloride solutions is close to those for Fe-As and Fe-Se in $\text{C-type}$ surface complexes formed by slightly bigger arsenate and selenate anions with hydrous ferric oxides ($\sim$3.25 Å, Manceau and Charlet, 1994; Manceau, 1995; Waychunas et al., 1993, 1995), and those for Fe-P found in Fe(III) phosphate minerals and aqueous solution ($\sim$3.20 Å, Rose et al., 1996, 1997a). The iron-iron coordination numbers corresponding to the Fe-Fe edge linkages are affected only slightly in the presence of aqueous silica both at acid and basic pH (Table 4). This suggests that at the early stages of hydrolysis, after the Fe-Fe dimer formation (Jolivet et al., 1994), aqueous silica is not capable of destroying these bonds significantly. The iron-iron edge distances in the silicate complexes found in this study (3.12 Å) are the same in both nitrate and chloride solutions at pH 2.8, suggesting that the edge-linked Fe polymers accommodate silica tetrahedra in a very similar way, independently of the nature of the ligand (Cl$^-$ versus NO$_3^-$). This confirms that neither chloride nor nitrate influence significantly Fe-Si interactions in dilute solutions typical of natural waters.

The numbers of Fe and Si neighbors around iron in the silicate complexes formed at acid pH ($N_{\text{Fe-Fe}}$ = 0.9–1.3; $N_{\text{Fe-Si}}$ = 1.0–2.0) is consistent with stoichiometries Fe$_2$Si$_{1.2}$ and Fe$_3$Si$_{2.3}$, corresponding to a mixture of Fe-Fe dimers and planar trimers linked to one to three silicate anions by their free double corners (Fig. 8). At basic pH, the Fe-Fe and Fe-Si coordination numbers found in this study imply that more polymerized Fe-Fe species, such as edge-sharing tetramers or bigger, are likely to form similar structures with silica. Note that the speciation of silica in 0.05-m Si solutions investigated in the present work is dominated by polymeric species ($\sim$80% of total Si) at acid pH and by monomeric silicate anions (>90% of total Si) at basic pH (see section 2.1). Nevertheless, the structural position of silicon atoms in the Fe-Si complexes appears to be similar at both acid and basic pH. This might reflect the preferential interaction of hydrolyzed Fe-polymers with monomeric Si(OH)$_4$. Indeed, reactions with big silicate polymers are likely to be hampered by slow kinetics and steric constraints (e.g., Swaddle, 2001). However, it cannot be excluded that Fe might interact with certain configurations of silicic acid polymers in acid solution. The structures of Fe-Si complexes proposed in this study are summarized in Figure 8.

By analogy with other tetrahedral anions like arsenate, selenate or phosphate, silicate can be expected to form also other types of bonds with Fe-octahedra, such as edge (type $^1E$, $R_{\text{Fe-Si}} \sim$ 2.8–2.9 Å) and single-corner (type $^1C$, $R_{\text{Fe-Si}} \sim$ 3.4–3.6 Å) linkages (e.g., see Manceau and Charlet, 1994; Manceau, 1995, for the linkage terminology). Nevertheless, none of these contributions was detected in this study. The $^1E$-linkages are not known in Fe(III) silicate and phosphate minerals. Thus, the edge-edge linkages between FeO$_6$ and SiO$_4$ are supposed to be negligible in solution, at least at the conditions of the present work. The existence of $^1C$ bonds in the Si-rich solutions investigated in this study, however, cannot be

---

**Fig. 8.** Schematic illustration of Fe(III) hydrolysis in Si-free aqueous solution, and structures of Fe-Si complexes proposed in this study for moderately concentrated Si-solutions. Octahedra represent the first Fe(O/OH/H$_2$O)$_6$ atomic shell; tetrahedra stand for the silicate moieties Si(O/OH)$_4$ of monomeric silicic acid or silica polymers.
corner Fe-O-Si bonds is also expected in the monomer complex FeO\(_2\)Si(H\(_2\)O\(_3\))\(^{2+}\) reported in acid solutions (Weber and Stumm, 1965; Olson and O’Melia, 1973; Reardon, 1979). Equilibrium calculations using the stability constant for this species derived from the studies cited above suggest that this complex should account for 50 ± 10% of total Fe at pH ~2.1 in the presence of 0.05-\(m\) Si(OH)\(_4\) (Fig. 9b). This percentage corresponds to an average number of Si neighbors of ~0.5 in the second coordination sphere of Fe at this pH. However, no Si neighbors could be found in the spectrum of a 0.05-\(m\) total Si solution at pH 2.1, in which silica was partially polymerized (see above). This might reflect both the difficulties to detect, by EXAFS spectroscopy, the light silicon in the disordered second shell environment of iron, and the lower affinity of Fe\(^{3+}\) cation for polymeric silicate species than for monomeric silicic acid (see above). More measurements at different Si concentrations are needed to confirm this hypothesis.

5. CONCLUDING REMARKS

The results of this study demonstrate that aqueous silica affects the hydrolysis of Fe(III) in dilute solution via the formation of iron silicate aqueous complexes. In these structures, silica substitutes for double-corner FeO\(_6\)-octahedra in iron oxy-hydroxide polymeric complexes existing at the early stages of Fe(III) hydrolysis, likely by forming C\(^{-}\)-type (double corner) complexes with small Fe oxy-hydroxide polymers whose structure consists of FeO\(_6\)-octahedra linked together by common edges. To our knowledge, this is the first quantitative evidence of the silica atomic environment in ferric silicate aqueous complexes.

The formation of soluble Fe-Si complexes delays the nucleation and growth of solid ferric oxy-hydroxides from aqueous solution. The significant silica concentrations found in these minerals in nature (e.g., Carlson and Schwertmann, 1981; Konhauser and Ferris, 1996) are likely to be a consequence of the aqueous Fe-Si complexing. However, the effect of silica on Fe(III) hydrolysis is significantly weaker than on Al\(^{3+}\) or Ga\(^{3+}\) hydrolysis. Due to the high affinity of Al and Ga for the tetrahedral coordination, these elements form much stronger covalent-bonded silicate complexes in which the metal is tetrahedrally coordinated even at acid pH and low silica concentrations (<0.01-\(m\) Si) (Pokrovski et al., 2002b). Ferric iron, in contrast, keeps an octahedral environment at moderate Si concentrations, and takes a tetrahedral coordination only in solutions highly enriched in silica (>0.1-\(m\) Si), in which Fe\(^{3+}\) may substitute for Si in the Si-polymer network. The observation, in high-temperature hydrothermal and metamorphic environments, of micas and amphiboles having significant proportions of Fe\(^{3+}\) in tetrahedral coordination (e.g., Dyar et al., 2001; Giuli et al., 2001) could thus be indicative of high silica activities during the formation of such minerals. In near-surface conditions, which are characterized by much lower aqueous silica activities, Fe\(^{3+}\) remains essentially hexa-coordinated in low-temperature oxy-hydroxides and clays (e.g., Sherman and Vergo, 1988; Manceau et al., 1998).

The geometry and structure of the silicate complexes formed at the surfaces of iron oxy-hydroxide minerals and colloids are expected to be similar to those found for the Fe-Si aqueous solutions investigated in this study. Via its linking to the free

Fig. 9. Predicted iron speciation in a 0.01-\(m\) ferric nitrate Si-free solution (a), and in the presence of 0.05-\(m\) monomeric silica (b) at 25°C as a function of solution pH. Calculations were performed using the stability constants for Fe hydroxide species reported by Baes and Mesmer (1976), and that for the iron-silica complex as the average value from Weber and Stumm (1965), Olson and O’Melia (1973), and Reardon (1979): Fe\(^{3+}\) + Si(OH)\(_4\)(aq) = FeO\(_2\)Si(H\(_2\)O\(_3\))\(^{2+}\) + H\(^+\), \(\log_{10} K (25°C, I = 0) = 0.03 ± 0.10\). Ionic strength was fixed at 0.15, and the activity coefficients of aqueous species were approximated by the extended Debye-Hückel equation with \(\sigma = 4.5\ \)Å for all charged species. Note that because of the lack of stability constants for iron oligomers bigger than trimers, this diagram represents a simplified image of the iron speciation at pH > 3-4. Consequently, the monomeric species at pH > 4 (dashed lines) are likely not dominant, and they are shown only for consistency with the calculations.

ruled out. Because of the expected higher degree of freedom associated with such single-corner bonds, their detection by EXAFS spectroscopy, which is very sensitive to disorder, is likely to be difficult. This is confirmed by the fact that no Si could be detected around the iron atom in the present study in a Si-rich solution (0.16-\(m\) Si) at pH 3. The presence of single
corners of FeO₆-octahedra, aqueous silica can decrease significantly the number of available sorption sites in Si-rich natural waters, and thus reduce both the incorporation of other trace anions and cations into iron hydroxides, and the bioavailability of their surfaces for Fe-metabolizing microorganisms (e.g., Meng et al., 2000; Santelli et al., 2001). The results on Fe-Si complex stoichiometries and structures obtained in this work may help improve models of silicate sorption by iron hydroxide phases, and abiotic or microbially catalyzed dissolution of iron silicate minerals.

Acknowledgments—We are grateful to the IF CRG commission of the ESRF for providing beam time and access to the synchrotron facility. We would like to thank Yvonne Soldo, Olivier Proux and Jean-Jacques Menthonnex for their professional assistance during XAFS measurements at BM 32 beamline. Oleg Pokrovsky is acknowledged for his generous help in solution preparation and spectra acquisition during the long and cold nights at the ESRF. Anastasia Borisova is thanked for her help in polyhedral modeling. We are indebted to Jacques Roux for corrections that greatly improved the presentation and clarity of this article. We thank Jérôme Rose, Glenn Waychunas, and Dave Sherman for their careful and constructive reviews of the manuscript.

Associate editor: M. L. Machesky

REFERENCES


