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Models for the estimation of Fe^{3+}/Fe_{tot} ratio in terrestrial and extraterrestrial alkali- and iron-rich silicate glasses using Raman spectroscopy

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Abstract

To develop Raman spectroscopy as a quantitative tool in both geosciences and planetary sciences the effect of iron oxidation state (Fe^{3+}/Fe_{tot}) on the Raman spectra of basaltic and pantelleritic glasses has been investigated. We have used remelted pantellerite from Pantelleria Island and synthetic iron-rich basaltic glasses [from Chevrel et al. (2014)].

The Raman spectra of pantelleritic glasses reveal dramatic changes in the high wavelength region of the spectrum (800–1200 cm^{-1}) as iron oxidation state changes. In particular the 970 cm^{-1} band intensity increases with increasing oxidation state of the glass (Fe^{3+}/Fe_{tot} ratio from 0.24 to 0.83). In contrast, Raman spectra of the basaltic glasses do not show the same oxidation state sensitivity (Fe^{3+}/Fe_{tot} ratio from 0.15 to 0.79). A shift, however, of the 950 cm^{-1} band to high wavenumber with decreasing iron oxidation state can be observed.

We present here two empirical parameterizations (for silica- and alkali-rich pantelleritic glasses and for iron-rich basaltic glasses) to enable estimation of the iron oxidation state of both anhydrous and hydrous silicate glasses (up to 2.4 wt% H_2O). The validation of the models derived from these parameterizations have been obtained using the independent characterization of these melt samples plus a series of external samples via wet chemistry.

The "pantelleritic" model can be applied within SiO_2, FeO, and alkali content ranges of ~69–75, ~7–9, and ~8–11 wt%, respectively. The "basaltic" model is valid within SiO_2, FeO, and alkali content ranges of ~42–54, ~10–22, and ~3–6 wt%, respectively.

The results of this study contribute to the expansion of the compositionally dependent database previously presented by Di Genova et al. (2015) for Raman spectra of complex silicate glasses. The applications of these models range from microanalysis of silicate glasses (e.g., melt inclusions) to handheld in situ terrestrial field investigations and studies under extreme conditions such as extraterrestrial (i.e., Mars), volcanic, and submarine environments.

Keywords: Silicate glasses, Raman spectroscopy, iron oxidation state, redox, basalt, pantellerite, planetary science, Mars

Introduction

The physico-chemical properties of silicate melts that govern magmatic and volcanic processes (melt generation, transport, and emplacement on the terrestrial planets) now have a long history of investigation (e.g., Richet 1984; Lange and Carmichael 1987, 1990; Persikov et al. 1990; Dingwell et al. 1996; Hess and Dingwell 1996; Papale 1999; Romano et al. 2001; Whittington et al. 2001; Dingwell 2006; Neuville 2006; Behrens and Zhang 2009; Di Genova et al. 2014a; Robert et al. 2014; Sehlke et al. 2014).

The wide range of chemical composition of magmatic and volcanic liquids means that to be useful the physico-chemical properties of these molten systems must be parameterized, directly or indirectly, in terms of chemical composition. Knowledge of the non-trivial nature of silicate melt structure and the enduring challenge of structure-property relationships for silicate melts has fueled a generation of investigations (e.g., Mysen et al. 1982; Stolper 1982; Neuville et al. 1993; Mysen 1997; Lee and Stebbins 2003; Stebbins 2008; Xue 2009; Malfait and Sanchez-Valle 2012; Di Genova et al. 2014b).

In all of this it has long been appreciated that the oxidation state and the structural role of iron in silicate melts plays a defining role affecting the melt structure and properties (e.g., Cukierman and Uhlmann 1974; Mysen et al. 1984; Dingwell and Virgo 1987, 1988; Lange and Carmichael 1987; Dingwell et al. 1988; Dingwell 1991; Toplis et al. 1994; Toplis and Carroll 1995; Giuli et al. 2011; Chevrel et al. 2013, 2014; Knipping et al. 2015).

Iron in silicate melts appears to exhibit elements of both network former and network modifier behavior. It is typically present in a range of coordination environments from tetrahedral (^{IV}Fe), through pentahedral (^{V}Fe) to octahedral (^{VI}Fe) and is always present in both reduced, ferrous (Fe^{2+}, network modifier), and oxidized, ferric (Fe^{3+}, network former) states (e.g., Mysen et al. 1984; Jackson et al. 1993; Wilke et al. 2001, 2006; Giuli et al. 2003; Magnien et al. 2008; Rossano et al. 2008).

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The ferric–ferrous ratio of equilibrated silicate melts depends on the temperature, redox state, and the chemical composition (including the volatile content) of the melt (Kress and Carmichael 1991; Mysen 1991; Ottonello et al. 2001; Botcharnikov et al. 2005; Moretti 2005; Giuli et al. 2012; Borisov et al. 2015; Cicconi et al. 2015). Thus a precise quantification of the ferric–ferrous ratio in silicate melts and glasses is a crucial constraint for the adequate parameterization of both the composition-dependence of physical properties (e.g., liquid viscosity and density) and the redox conditions prevailing in magmatic systems.

The most widely employed standard techniques for the direct determination of Fe^{3+}/Fe_{tot} ratio in silicate glasses are wet-chemical analyses, ^{57}Fe Mössbauer spectroscopy and XANES [see Berry et al. (2003) and Mysen and Richet (2005) for reviews]. Wet chemistry is considered the most precise method, however, it is destructive and it consumes a relatively large amount of sample (in the order of 100–500 mg) for a precise Fe^{2+} concentration determination (±0.02). Standard Mössbauer spectroscopy requires powdered samples (in the order of 50–100 mg) for an accurate estimation of Fe^{3+}/Fe_{tot} (±0.02) and, in addition, it is relatively limited in spatial resolution (McCammon et al. 1991; Berry et al. 2003 and references therein). Fe *K*-edge XANES spectroscopy requires a smaller amount of material and it has been employed also on small amount of glass and it is characterized by a high spatial resolution (micrometers). Nevertheless, despite the wide applicability of this technique, three main points must be considered: (1) the fitting procedure of the Fe pre-edge peak is not easy and the Fe^{3+}/Fe_{tot} estimation is associated with a high error (±0.05) respect to wet chemistry and Mössbauer; (2) for low amount of total iron, photoreduction by synchrotron beam has been reported (Campeny et al. 2015); and (3) XANES spectroscopy is not easily accessible as it requires beam time at a synchrotron radiation facility.

Raman spectroscopy is a technique commonly used for studying the structure of silicate glasses and melts (Neuville et al. 2014 for a review). It offers the advantages that (1) little or no sample preparation is required, (2) the technique is non-destructive, and (3) can be used to perform in situ and remotely controlled analysis under extreme conditions like, for example, submarine environment or on planetary surfaces [see Di Genova et al. (2015) and references therein for a review].

Only one study (Di Muro et al. 2009) has raised the possibility of retrieving information on the Fe^{3+}/Fe_{tot} ratio of natural silicate glasses (pantelleritic and basaltic compositions) by Raman spectroscopy.

Results from Di Muro et al. (2009) show a dependence of Raman spectra for some remelted silicate glasses on iron oxidation state. They demonstrate the existence of a relationship between the measured Fe^{3+}/Fe_{tot} ratio (by wet chemistry and XANES spectroscopy) and the Raman parameters derived by spectra deconvolution (e.g., area%, band position, and bands intensity ratio). In particular, because of the significant sensitivity of Raman spectra of pantelleritic samples with the variation in Fe^{3+}/Fe_{tot} ratio, the authors concluded that peralkaline glasses represent an ideal system to define a Raman model to estimate the iron oxidation state of samples. On the other hand, their results on basaltic samples demonstrated the decreasing sensitivity of the glass structure, and consequently of Raman spectra, with changing redox conditions of the system.

Unfortunately, as those authors reported, this approach depends strongly on both the spectra fitting procedure (i.e., spectrum deconvolution) and the chemical composition of samples [see Rossano and Mysen (2012) and Neuville et al. (2014) for reviews].

Recently, Di Genova et al. (2015) have demonstrated that the chemical composition of natural silicate glasses could be approximated using Raman spectroscopy *without* the use of a spectra deconvolution procedure.

In this work, we combine wet-chemical analysis and Raman spectroscopy to track the evolution of the Raman spectra as a function of Fe^{3+}/Fe_{tot} ratio of remelted and synthetic silicate glasses. The evolution of the acquired Raman spectra has been parameterized using the empirical criterion presented in Di Genova et al. (2015), which is based on an ideal mixing equation, to provide two Raman spectroscopy models for determining the Fe^{3+}/Fe_{tot} ratio of silica-alkali-rich and iron-rich basalt silicate glasses (anhydrous and mildly hydrous) in terrestrial and extra-terrestrial environments.

Experimental methods

Starting material

In this study, the starting material consist of (1) anhydrous, crystals, and bubble-free silica- and alkali-rich glasses of pantelleritic composition (i.e., peralkaline rhyolite, Fsp sample series) with different Fe^{3+}/Fe_{tot} ratio that were prepared by melting a natural sample from Cala di Tramontana (Pantelleria Island), at 1500 °C and homogenized by continuous stirring in a concentric cylinder apparatus at 1 atm until the melt was free of bubbles and crystals; (2) anhydrous, crystals, and bubble-free iron-rich (up to ~20 wt% FeO_{tot}) basaltic glasses (AdMB and LDM series) representative of the known diversity of martian basalts with different Fe^{3+}/Fe_{tot} ratios from Chevrel et al. (2014). The AdMB chemical composition corresponds to the chemical analyses of the Adirondack class rock (Gusev plains, Mars) as given by Ming et al. (2008). The LDM chemical composition is based on equilibrium melting calculations of a primitive mantle composition [see Baratoux et al. (2011) and Chevrel et al. (2014) for details].

Both sets of samples were synthetized at different oxygen fugacity, f_{O_2}, in a gas-mixing furnace to obtained glasses with different Fe^{3+}/Fe_{tot} ratio (as described in Chevrel et al. 2014). The furnace is equipped with a gas tight alumina muffle tube and CO-CO_2 gas mixing line. The f_{O_2} was controlled by CO-CO_2 gas mixtures and monitored by an yttrium-stabilized, zirconia-based oxygen electrode calibrated against air and pure CO_2. At least 24 h was required to permit melt equilibration for each oxidation step. Sampling was performed after each equilibration by a "dip quench" technique that consisted of inserting an alumina-oxide rod into the melt, which was then withdrawn and plunged into distilled water to ensure a rapid quench. All glasses were verified to be free from crystals by optical and electron microscopy.

Iron oxidation state

The iron oxidation state of the investigated samples was determined by redox titration using potassium dichromate ($K_2Cr_2O_7$): a wet-chemistry method based on a simple potentiometric titration (Giuli et al. 2011). The standard materials used for the evaluation of the standard deviation of the measurements were a standard rock basalt (BHVO-1, USGS standard, Lit. 8.58 wt% FeO) and a synthetic standard containing 18.8 wt% of FeO. The standard deviation of the measurements was determined to be ±1.5%. Each measurement was performed with approximately 25 mg of sample.

Chemical analysis

The concentrations of major elements were measured with a Cameca SX100 electron microprobe analyzer (EMPA) of the Department of Earth and Environmental Sciences at the University of Munich. The chemical analyses were carried out at 15 kV acceleration voltage and 5 nA beam current. A defocused 10 µm beam was used for all elements to minimize alkali loss. Synthetic wollastonite (Ca, Si), periclase (Mg), hematite (Fe), corundum (Al), natural orthoclase (K), and albite (Na) were used as standards, and matrix correction was performed by

PAP procedure (Pouchou and Pichoir 1991). The precision was better than 2.5% for all analyzed elements. To evaluate the chemical homogeneity of glasses 25 chemical analyses were performed for each sample. As reported in Chevrel et al. (2014), a liquid immiscibility in the iron-rich basalt glasses can be observed. This aspect does not represent a limitation in our study, as the Raman spot size is much smaller than the characteristic dimension of the liquid-liquid immiscibility (from tens to hundreds of micrometers).

Raman spectroscopy

Raman spectra were obtained using a micro-Raman spectrometer (HORIBA; XploRa-Raman-System) equipped with three lasers (red, green, and NIR). A green argon ion laser (532 nm), which provided a power at the sample surface of ~2.5 mW, was focused through the 100× objective to a ~1 μm spot. The Raman system was set with a laser attenuation of 25% in respect to the total laser power, 1200T grating, exposure time 30 s (3 times), and confocal hole of 300 μm and slit of 200 μm. Backscattered Raman radiation was collected over a range from 150 to 1400 cm^{-1} and elastically scattered photons were suppressed via a sharp edge filter. The instrument was calibrated using a silicon standard.

All the acquired spectra have been corrected for the wavelength of excitation source and temperature dependence of the Raman intensity according to Shuker and Cammon (1970) and Long (1977) approaches. Finally, a background subtraction technique has been applied to all the spectra according to the strategy reported in Di Genova et al. (2015) where two zones devoid of peaks were chosen to constrain the cubic baseline (from 50 to ~250 and ~1250 to 1500 cm^{-1}).

Results

Chemical composition and iron oxidation state

Measured chemical compositions and Fe^{3+}/Fe_{tot} ratio of pantelleritic (this study) and basaltic (Chevrel et al. 2014) glasses are reported in Table 1.

Additionally, in Figure 1 we report in a TAS diagram the chemical compositions of both the pantelleritic and basaltic end-members (Fsp_1, Fsp_9 and AdMB-S2, LDM-S5, respectively).

Pantelleritic samples include nine different glasses with different Fe^{3+}/Fe_{tot} ratios ranging between 0.24 and 0.83, and having an agpaitic index [$(Na_2O+K_2O)/Al_2O_3$ mol%] of around 1.3. Main oxides range between ~72–75 wt% SiO_2, ~7–9 wt% FeO_{tot}, ~9 wt% Al_2O_3, and alkali (Na_2O+K_2O) between ~8 and 11 wt%.

Basaltic samples are highly enriched in iron [FeO_{tot} ranging from ~18 to ~20 wt%] as analyzed on Mars [see Chevrel et al. (2014)] and include four glasses having different Fe^{3+}/Fe_{tot} ratio ranging between 0.15 and 0.79. Specifically, we used three AdMB samples (AdMB-S2, S5, and S6) and one sample (LDM-S5) belonging to the LDM series that represents the sample with the lowest Fe^{3+}/Fe_{tot} ratio among the analyzed samples in Chevrel et al. (2014). SiO_2 varies between ~45–48 wt%, Al_2O_3 is ~11 wt%, and alkali and alkaline earth (MgO+CaO) range between ~3–4 and ~18–20 wt%, respectively.

Raman spectra: Effect of the chemical composition

Figures 2 and 3 show the Raman spectra acquired, corrected for the wavelength of the excitation source and temperature. The raw spectra are reported in Figures 2a and 3a, while Figures 2b and 3b show the normalized spectra (to 100 arbitrary units) vertically superimposed as a function of the Fe^{3+}/Fe_{tot} ratio.

The collected Raman spectra show three main bands: the low-wavenumber region (LW ~250–650 cm^{-1}), the mid-wavenumber region (MW ~650–850 cm^{-1}) and in the high-wavenumber region (HW ~850–1250 cm^{-1}).

The LW region is usually assigned to vibrations of bridging O atoms (BO) with three-, four-, five-, six-, or higher-membered rings of tetrahedra present in silicate networks (e.g., Bell et al. 1968; Mysen et al. 1980; McMillan and Piriou 1982; Seifert et al. 1982; Neuville and Mysen 1996; Pasquarello et al. 1998; Mysen 2003; Umari et al. 2003; Neuville et al. 2014). The HW region yields information about the vibration of T–O^- bonds [where T refers to fourfold-coordinated cations (Si^{4+}, Al^{4+}, Fe^{3+}) and O^- non-bridging oxygen, NBO] and the structural effect of the network-modifying or charge balancing cations (e.g., Bell and Dean 1972; Furukawa et al. 1981; McMillan 1984; Mysen 2003; Mysen and Toplis 2007; Neuville et al. 2014). For a detailed discussion of structural interpretation of Raman spectra we refer to Rossano and Mysen (2012) and Neuville et al. (2014).

Overall, the LW region of pantelleritic samples (Fig. 2a) shows a well-defined band between 250 and 650 cm^{-1} with a peak located around 470 cm^{-1} and a shoulder at 590 cm^{-1}. In contrast, the LW region of basaltic spectra (Fig. 3a) shows an asymmetric band centered around 550 cm^{-1} and overlapping with the MW region.

In the MW region, a symmetric band occurs between 670 and 850 cm^{-1} in the spectra of all investigated samples and shows the highest intensity in the basaltic spectra.

Concerning the HW region, the pantelleritic spectra display a complex behavior of the band located between 850 and 1250 cm^{-1}. The most oxidized sample (Fsp_1) shows a peak located at 970 cm^{-1} and two shoulders at 1040 and 1150 cm^{-1} while the most reduced sample (Fsp_9) clearly shows a peak at around 1040 cm^{-1} with two shoulders at 970 and 1150 cm^{-1}.

Table 1. Chemical composition and iron oxidation state of analyzed glasses

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Tot.	Fe^{3+}/Fe_{tot} [b]	Fe^{3+}/Fe_{tot}^{calc} [c]
Fsp_1	72.53	0.44	8.70	9.02	0.34	0.17	0.45	4.59	4.09	0.00	100.33	0.83	0.86
Fsp_2	71.89	0.43	8.78	8.78	0.35	0.16	0.43	4.37	4.01	0.00	99.20	0.74	0.76
Fsp_3	72.94	0.42	8.92	8.55	0.37	0.17	0.44	4.46	4.10	0.00	100.37	0.58	0.58
Fsp_4	71.93	0.43	8.97	8.93	0.37	0.17	0.46	4.72	4.18	0.00	100.16	0.62	0.56
Fsp_5	73.75	0.41	9.06	7.73	0.30	0.15	0.37	4.08	3.94	0.00	99.79	0.69	0.69
Fsp_6	73.11	0.43	8.97	8.34	0.37	0.17	0.47	4.55	4.18	0.00	100.59	0.40	0.43
Fsp_7	73.44	0.43	9.05	7.71	0.35	0.17	0.40	4.08	3.99	0.00	99.62	0.35	0.33
Fsp_8	74.62	0.45	9.05	7.17	0.38	0.18	0.45	4.06	4.05	0.00	100.41	0.26	0.27
Fsp_9	74.24	0.44	9.01	7.04	0.36	0.17	0.47	4.19	4.14	0.00	100.06	0.24	0.24
AdMB-S2[a]	46.77	0.61	10.93	19.65	0.44	9.23	8.73	2.88	0.18	0.57	100.00	0.79	0.79
AdMB-S5[a]	47.46	0.58	10.98	19.41	0.44	8.97	8.59	2.84	0.18	0.57	100.00	0.52	0.49
AdMB-S6[a]	47.62	0.64	11.13	18.95	0.43	9.13	8.53	2.84	0.17	0.57	100.00	0.37	0.36
LDM-S5[a]	45.17	0.71	10.47	18.09	0.14	11.28	8.96	3.91	0.29	0.98	100.00	0.15	0.15

[a] From Chevrel et al. (2014) (normalized to 100 wt%).
[b] Obtained by wet chemistry.
[c] Calculated Fe^{3+}/Fe_{tot} ratio using Equation 2.

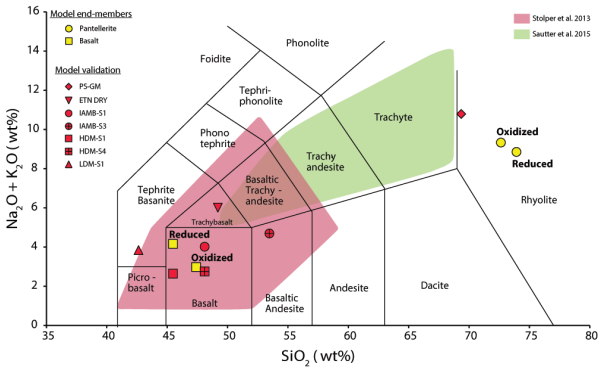

FIGURE 1. Total alkali vs. SiO_2 contents in wt% (TAS) diagram showing the chemical composition of glasses used in this study. Yellow symbols represent the input chemical composition (oxidized and reduced) used to develop the Raman models (Eq. 1). Red symbols represent the samples used for the model validation. Red and green areas show the interval of chemical compositions measured on Mars and from martian meteorites according to Stolper et al. (2013) and Sautter et al. (2015).

In contrast, for the basaltic samples, the band occurs between 800 and 1200 cm^{-1} with a peak between 950 and 966 cm^{-1} a shoulder located at ~1040 cm^{-1} and show less variation with oxidation as detailed below.

Raman spectra: Effect of Fe^{3+}/Fe_{tot} ratio

To explore the evolution of Raman spectra with the oxidation state, and provide Raman models to estimate the Fe^{3+}/Fe_{tot} ratio, we vertically superimposed the normalized Raman spectra as a function of Fe^{3+}/Fe_{tot} ratio (Figs. 2b and 3b).

Pantelleritic glasses

Figure 2b shows the normalized Raman spectra as a function of the Fe^{3+}/Fe_{tot} ratio. In the LW region, both the intensities of the peak located at ~470 cm^{-1} and the shoulder located at ~590 cm^{-1} decrease with increasing the Fe^{3+}/Fe_{tot} ratio. Similarly in the MW region the peak located at ~800 cm^{-1} decreases in intensity with increasing the Fe^{3+}/Fe_{tot}

The HW region exhibits a remarkable variation of the Raman spectrum with Fe^{3+}/Fe_{tot} ratio. Indeed, with increasing Fe^{3+}/Fe_{tot} ratio, the wavelength position of the band centroid shifts toward low wavenumbers: from 1040 cm^{-1} (Fsp_9, $Fe^{3+}/Fe_{tot} = 0.24$) down to 970 cm^{-1} (Fsp_1, $Fe^{3+}/Fe_{tot} = 0.83$) and the shoulder located at 970 cm^{-1} dramatically decreases in intensity. Concurrently, the shoulder located at 1150 cm^{-1} decreases in intensity with increasing Fe^{3+}/Fe_{tot} ratio. The most oxidized sample (Fsp_1) therefore shows a peak located at 970 cm^{-1} and two shoulders at 1040 and 1150 cm^{-1}, while the most reduced sample (Fsp_9) clearly shows a peak at around 1040 cm^{-1} with two shoulders at 970 and 1150 cm^{-1}.

Basaltic glasses

Although the Raman spectra of the basaltic samples exhibit a weaker variation with Fe^{3+}/Fe_{tot} ratio than the pantelleritic samples, some variations can be pointed out (Fig. 3b).

The intensity in LW and MW region increases with increasing Fe^{3+}/Fe_{tot} ratio. In the HW region, the main peak position shifts toward low wavenumber with increasing the Fe^{3+}/Fe_{tot} ratio.

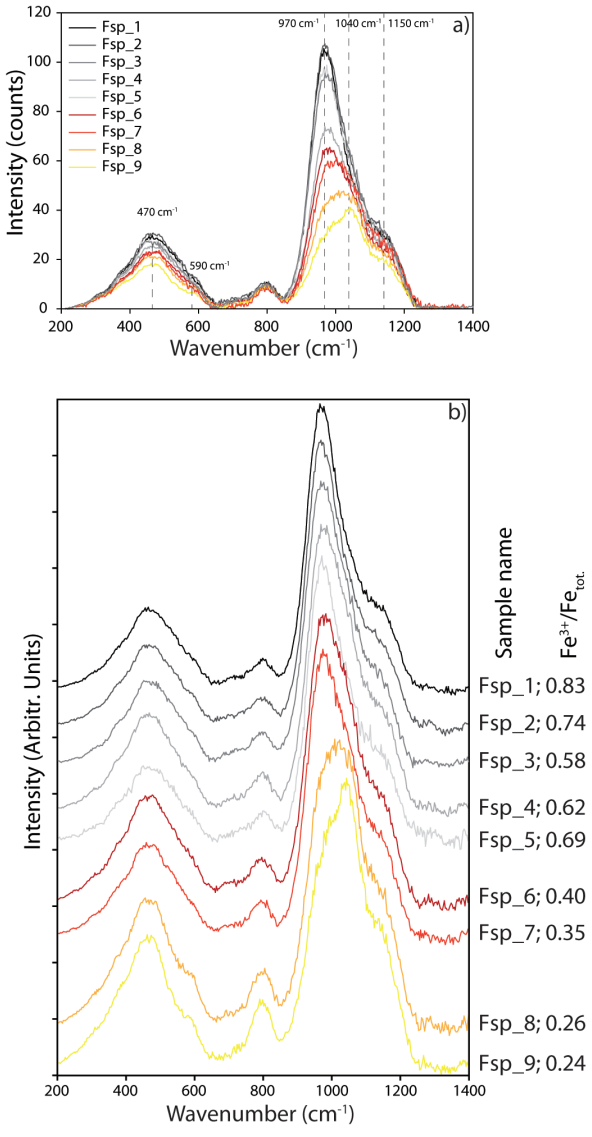

FIGURE 2. (**a**) Raw Raman spectra after a cubic baseline correction of silica-alkali-rich samples (Fsp, pantellerite). Vertical dashed lines represent the main peaks and shoulders of the spectra. (**b**) Raman spectra corrected according to Equation 2 and normalized to the most intense peak.

Indeed, the reduced end-member (LDM-S5, $Fe^{3+}/Fe_{tot} = 0.15$) exhibits the peak at 966 cm^{-1} while the oxidized end-member (AdMB-S2, $Fe^{3+}/Fe_{tot} = 0.79$) has the peak at 950 cm^{-1}. The samples characterized by an intermediate iron oxidation state show intermediate main peak position at 963 and 961 cm^{-1} for AdMB-S6, $Fe^{3+}/Fe_{tot} = 0.37$ and for AdMB-S5, $Fe^{3+}/Fe_{tot} = 0.52$, respectively. Additionally, a decrease of the shoulder intensity (~1040 cm^{-1}) occurs with increasing Fe^{3+}/Fe_{tot} ratio.

DISCUSSION

The results presented here generally agree with those of Di Muro et al. (2009). Pantelleritic Raman spectra in this study show

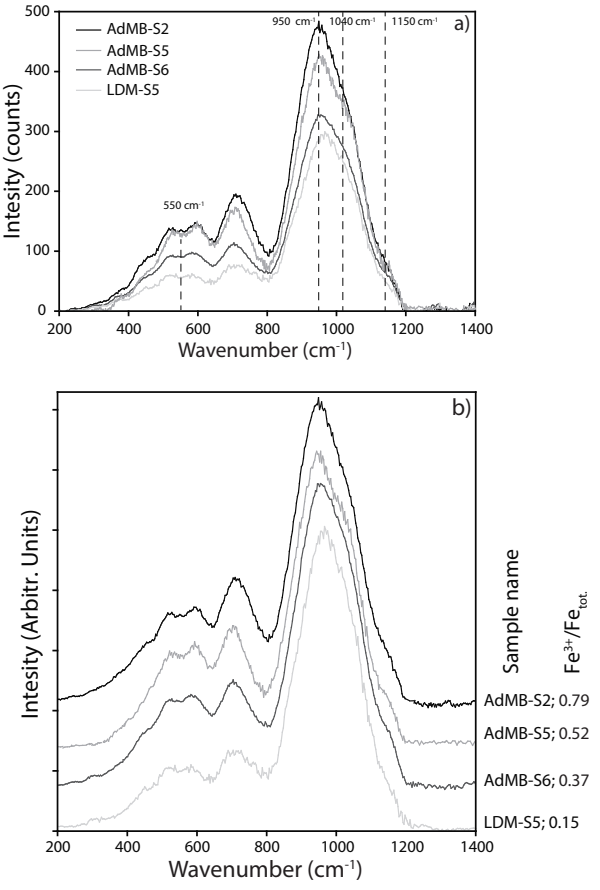

FIGURE 3. (**a**) Raw Raman spectra after a cubic baseline correction of iron-rich samples (AdMB and LDM, martian basalts). Vertical dashed lines represent the main peaks and shoulders of the spectra. (**b**) Raman spectra corrected according to Equation 2 and normalized to the most intense peak.

a dramatic variation with changing the Fe^{3+}/Fe_{tot} ratio while a weak sensitivity of Raman spectra is observed for the basaltic glasses with changing iron oxidation state.

Our approach differs however in one important aspect from that employed by Di Muro et al. (2009). As noted above, we avoid the highly disputed use of deconvolution bands (Rossano and Mysen 2012; Neuville et al. 2014). Instead we adopt the criterion reported in Di Genova et al. (2015) based on an empirical approach to parameterize Raman spectra using an ideal mixing equation (reported below). This approach provides a robust strategy to determine the iron oxidation state of glasses, independent of the chemical composition of the samples investigated. Furthermore, using this approach, together with iron-rich basaltic glasses (suitable for planetary science studies), the limitation due the low sensitivity of Raman spectra to different iron oxidation states (for depolymerized compositions like basalt) is overcome.

Parameterization of the evolution of Raman spectra

To evaluate Raman spectroscopy as a tool to estimate the iron oxidation state of glasses we combine the acquired Raman spectra (Figs. 2b and 3b) with measured Fe^{3+}/Fe_{tot} ratios (Table 1) using the model presented in Di Genova et al. (2015).

We used an empirical formula (Eq. 1) previously reported in Di Genova et al. (2015) to parameterize the Raman spectra as a function of a fit parameter (R_p). Specifically we assume that an acquired Raman spectrum can be approximate combining two end-members Raman spectra with the Raman parameter R_p:

$$Y = E_{ox} \cdot R_P + E_{RED}(1 - R_p) \quad (1)$$

where Y represents the acquired Raman spectrum of the investigated sample, and E_{ox} and E_{RED} represent the Raman spectra end-members, namely the most oxidized (Fsp_1 and AdMB-S2) and the most reduced (Fsp_9 and LDM-S5) samples for the pantelleritic and basaltic glasses, respectively. The R_p fit parameter was calculated for each acquired Raman spectra using Equation 1, and has been reported and plotted in Table 2 and Figure 4 together with the measured Fe^{3+}/Fe_{tot} ratios.

It must be noted that the R_p parameter is equal to 1 when only the most oxidized end-members are considered (Fsp_1 and AdMB-S2) and, on the other hand, is equal to 0 when only the most reduced end-members are considered (Fsp_9 and LDM-S5).

The two different compositions clearly exhibit trends with respect to the calculated Raman parameter vs. Fe^{3+}/Fe_{tot} ratio. For this reason, these trends were parameterized as a function of the Raman parameter (R_p) to calculate the Fe^{3+}/Fe_{tot} ratio of glasses.

Raman models to calculate the Fe^{3+}/Fe_{tot} ratio of silicate glasses

We parameterized the Fe^{3+}/Fe_{tot} ratio as a function of R_p parameter using the following equation:

$$\frac{Fe^{3+}}{Fe_{tot}} = \sqrt{\frac{(a + cR_p)}{(1 + bR_p)}} \quad (2)$$

where a, b, and c are the best-fit parameters. Finally, using the Equation 2 with the fit parameters reported in Table 3 (for pantelleritic and basaltic glasses) and the calculated R_p parameters using Equation 1 (Table 2), we can accurately estimate the Fe^{3+}/Fe_{tot} ratio of our samples simply using the acquired Raman spectra. In Table 1 we report the calculated Fe^{3+}/Fe_{tot} ratios, while in Figure 5 we show the comparison between measured and calculated iron oxidation state of our samples.

Validation of the models

To validate our approach, we have investigated 11 other samples. For this purpose, we have used six natural glasses, anhydrous and water-bearing, with different Fe^{3+}/Fe_{tot} ratios: three pantelleritic glasses from Pantelleria Island (PS series in Di Genova et al. 2013, 2014a) and three basaltic glasses from Etna (ETN series in Di Genova et al. 2014a). In addition, we have used five iron-rich basaltic glasses with different Fe^{3+}/Fe_{tot} ratios (analogs for extra-terrestrial basalt, from the IAMB, LDM, HDM series in Chevrel et al. 2014). Chemical compositions are reported in Table 4 together with the measured iron oxidation state and water content and, in addition, are shown in a TAS diagram (Fig. 1).

The acquired Raman spectra are reported in Figure 6. In Table

TABLE 2. Calculated R_p parameter using Equation 1

Sample	Fe^{3+}/Fe_{tot}	R_p
Fsp_1	0.83	1.000
Fsp_2	0.74	0.947 (0.004)
Fsp_3	0.58	0.793 (0.008)
Fsp_4	0.62	0.770 (0.009)
Fsp_5	0.69	0.903 (0.007)
Fsp_6	0.40	0.564 (0.011)
Fsp_7	0.35	0.314 (0.014)
Fsp_8	0.26	0.104 (0.013)
Fsp_9	0.24	0.000
AdMB-S2	0.79	1.000
AdMB-S6	0.37	0.684 (0.017)
HDM-S1	0.77	1.000 (0.011)
LDM-S5	0.15	0.000

4 we report, for each sample, the chemical compositions, the measured iron oxidation state, and water content together with the calculated R_p parameters using Equation 1 and the estimated Fe^{3+}/Fe_{tot} ratio using our models (Eq. 2 and fit parameters in Table 3). A comparison between the estimated and the measured Fe^{3+}/Fe_{tot} ratio is reported in Figure 7. As can be seen in the figure the calculated Fe^{3+}/Fe_{tot} ratio of the investigated sample are well

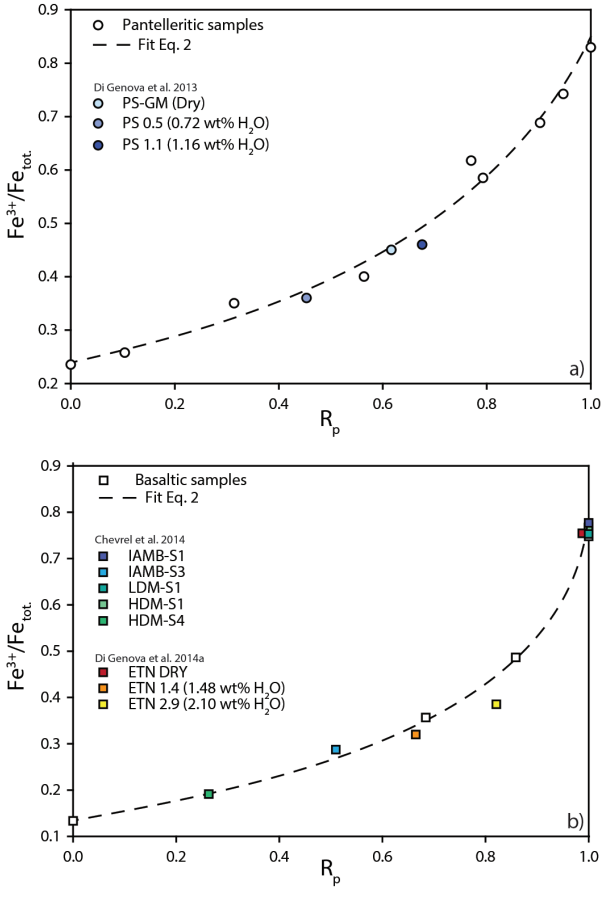

FIGURE 4. Measured iron oxidation states as a function of the calculated Raman parameter (R_p) using Equation 1 for (**a**) pantelleritic and (**b**) basaltic samples. Lines represent the fits obtained using Equation 2 and fit parameters reported in Table 3. White symbols represent the samples used for model parameterization and colored symbols represent external samples used for model validation.

TABLE 3. Fit parameters used to parameterize the Fe^{3+}/Fe_{tot} ratio (Eq. 2) as a function of the R_p parameter (Eq. 1)

	a	*b*	*c*	R^2
Pantellerite	0.0571 (0.0061)	–0.8189 (0.0570)	0.0760 (0.0288)	0.984
Basalt	0.0223 (0.0039)	–0.9007 (0.0300)	0.0391 (0.0131)	0.996

in accordance with the measured values.

Upon inspection of Table 4 it is possible to assess quantitatively the validity of our models to determine the iron oxidation state of silicate glasses. In particular, the anhydrous pantelleritic glass (PS-GM) exhibits a measured Fe^{3+}/Fe_{tot} ratio of 0.36, while the calculated ratio using our model is 0.38. Concerning the anhydrous analogs extra-terrestrial basalt (IAMB, LDM, HDM series), the estimated Fe^{3+}/Fe_{tot} ratio is 0.79, 0.28, 0.79, 0.21, and 0.79 for IAMB-S1 and -S3, HDM-S1 and -S4 and LDM-S1 samples, respectively, while the measured Fe^{3+}/Fe_{tot} ratios are 0.79, 0.31, 0.77, 0.20, and 0.77.

Although our models have been developed using volatile-free samples, we used water-bearing samples (PS 0.5, PS 1.1, ETN 1.4, and ETN 2.9) to verify the accuracy of our models in predicting the iron oxidation state. It must be noted that a water-bearing glass represent an extreme scenario for testing our model as the water has the biggest effects, among all the magmatic volatiles (e.g., H_2O, CO_2, F, Cl) in affecting the silicate structure (Di Genova et al. 2014a and references therein) and, consequently, the Raman spectra.

In particular, for pantelleritic water-bearing glasses, our model accurately predicts the measured Fe^{3+}/Fe_{tot} ratio. Indeed, sample PS 0.5, characterized by a water content of 0.72 wt%, exhibits a Fe^{3+}/Fe_{tot} ratio of 0.46. while the calculated Fe^{3+}/Fe_{tot} ratio is 0.49. At the same time, sample PS 1.1 that is characterized by a higher water content (1.16 wt%) with respect to PS 0.5, exhibits a Fe^{3+}/Fe_{tot} ratio of 0.45 while the calculated ratio is 0.47. We did not validate our model to predict the oxidation state of a pantelleritic samples with a high water content (2.10 wt% H_2O). The difficulty to estimate the Fe^{3+}/Fe_{tot} ratio of such water-rich samples is probably due the large effect of this amount of water on the Raman spectrum.

Regarding the basaltic samples, the model can accurately predict the iron oxidation state (measured Fe^{3+}/Fe_{tot} = 0.32, calculated = 0.35) for sample with minor water content (ETN 1.4, H_2O 1.48 wt%), however the model shows large errors when the sample with the highest water content is considered (ETN 2.9, H_2O 2.40 wt%). The measured Fe^{3+}/Fe_{tot} ratio is 0.39, while the calculated ratio is 0.48.

For these reasons we stress that care must be taken in applying our models to water-rich samples (i.e., higher than 2.10 and 2.40 wt% for pantelleritic and basaltic samples), because the strong effects of water on the glass structure and, therefore, on the Raman spectra.

How to use the models

The Excel version of our models is provided as Supplemental Material[1]. First of all, a Raman spectrum has to be acquired, and we suggest setting the Raman system on how it is reported in

[1] Deposit item AM-16-45534, Supplemental Material, Excel calculator for the estimation of iron oxidation state in silicate glasses. Deposit items are free to all readers and found on the MSA web site, via the specific issue's Table of Contents (go to http://www.minsocam.org/MSA/AmMin/TOC/).

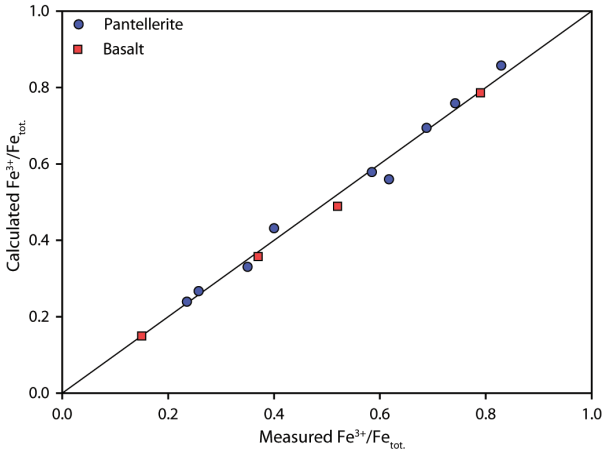

FIGURE 5. Comparison between measured Fe^{3+}/Fe_{tot} ratio using wet chemistry and calculated Fe^{3+}/Fe_{tot} using our proposed Raman models (Eq. 2 and fitting parameters of Tables 2 and 3) for the samples used in this study. Fe^{3+}/Fe_{tot} ratios are reported in Table 1.

the Raman Spectroscopy paragraph. Subsequently, the following correction has to be applied to the acquired Raman spectrum [see Shuker and Cammon (1970) and Long (1977) for the theoretical background]:

$$I = I_{obs} \cdot \left\{ v_0^3 \cdot v \frac{\left[1 - \exp\left(-hcv / kT\right)\right]}{\left(v_0 - v\right)^4} \right\} \quad (3)$$

where I_{obs} is the acquired Raman spectra; h is the Planck constant, $h = 6.62607 \times 10^{-34}$ J s; k is the Boltzmann constant; $k = 1.38065 \times 10^{-23}$ J K^{-1}; c is the speed of light, $c = 2.9979 \times 10^{10}$ cm s^{-1}; T is the absolute temperature, ν_0 is the wavenumber of the incident laser light (10^7/532 for the green laser), and ν is the measured wavenumber in cm^{-1}.

After applying the correction, the background subtraction has to be applied to the acquired spectrum (see the Raman Spectroscopy paragraph) together with an intensity normalization to 100 (arbitrary units).

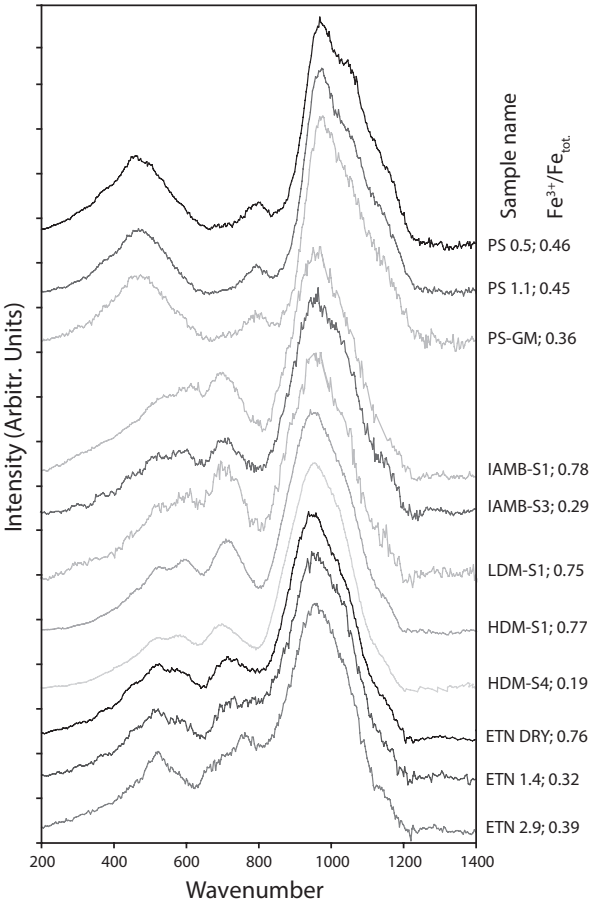

FIGURE 6. Long-corrected and normalized Raman spectra of samples used to validate our Raman models. PS and ETN samples are from Di Genova et al. (2013, 2014a), while the remaining samples are from Chevrel et al. (2014).

Finally, before using the Excel file[1], it is important to verify that the three different Raman spectra (two end-members spectra and the sample spectrum) have to be necessarily characterized by the same X values (cm^{-1}).

TABLE 4. Chemical composition and iron oxidation state of the analyzed external samples used to test the proposed Raman model; the calculated iron oxidation state using the Equation 2 and the calculated Raman parameter (R_p) are also reported

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	H_2O	Total	Fe^{3+}/Fe_{tot}	R_p[b]	Fe^{3+}/Fe_{tot}^{calc}[c]
PS-GM[a]	69.21	0.50	9.18	8.63	0.32	0.08	0.60	6.52	4.35	0.04	–	0.00	99.43	0.36	0.640 (0.012)	0.38
PS0.5[d]	70.02	0.49	9.18	8.30	0.39	0.08	0.59	5.94	3.96	0.04	0.01	0.72	99.72	0.46	0.454 (0.018)	0.49
PS1.1[d]	69.78	0.49	9.09	8.44	0.37	0.08	0.58	5.74	3.99	0.02	0.01	1.16	99.75	0.45	0.676 (0.013)	0.47
IAMB-S1[e]	48.14	1.09	8.52	21.31	0.41	9.33	6.45	3.32	0.57	0.86	–	0.00	100.00	0.79	1.000 (0.082)	0.79
IAMB-S3[c]	53.59	1.03	9.18	16.62	0.34	8.05	5.73	3.85	0.77	0.86	–	0.00	100.00	0.31	0.510 (0.022)	0.28
HDM-S1[e]	45.23	0.56	10.34	21.04	0.12	11.04	8.27	0.20	2.61	0.60	–	0.00	100.00	0.77	1.000 (0.052)	0.79
HDM-S4[e]	47.35	0.55	10.75	18.46	0.11	11.04	8.21	0.19	2.73	0.60	–	0.00	100.00	0.20	0.263 (0.010)	0.21
LDM-S1[e]	42.69	0.68	10.11	21.77	0.15	10.98	8.72	3.60	0.27	1.03	–	0.00	100.00	0.77	1.000 (0.038)	0.79
ETN DRY[d]	48.95	1.67	17.00	10.08	0.24	5.54	10.18	3.72	1.85	0.01	0.47	0.00	99.71	0.76	0.988 (0.024)	0.74
ETN 1.4[d]	47.96	1.65	16.68	10.17	0.22	5.39	10.09	3.66	1.83	0.02	0.53	1.48	99.68	0.32	0.671 (0.035)	0.35
ETN 2.9[d]	47.90	1.61	16.62	10.15	0.20	5.29	9.92	3.59	1.78	0.01	0.47	2.40	99.94	0.39	0.845 (0.043)	0.48

[a] From Di Genova et al. (2013).
[b] Raman parameter calculated according to Equation 1.
[c] Calculated Fe^{3+}/Fe_{tot} ratio using Equation 2.
[d] From Di Genova et al. (2014a).
[e] From Chevrel et al. (2014).

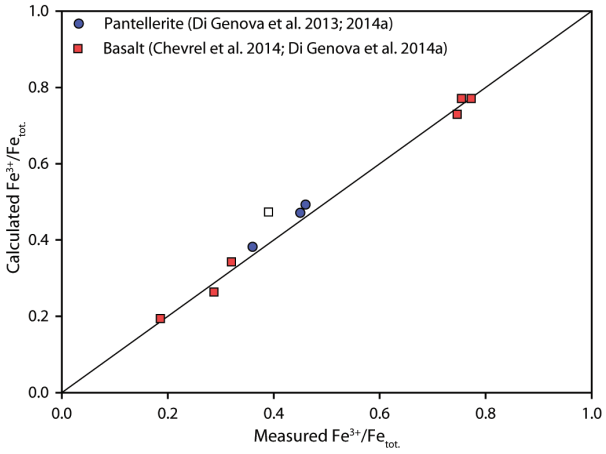

FIGURE 7. Comparison between measured Fe^{3+}/Fe_{tot} ratio using wet chemistry and calculated Fe^{3+}/Fe_{tot} ratio using our Raman models (Eq. 2) for the samples used to validate the models. Fe^{3+}/Fe_{tot} ratios and Raman parameters are reported in Table 4. The white square represents the basaltic sample (ETN 2.9) with the highest water content (H_2O 2.40 wt%) for which our model shows the highest error in the Fe^{3+}/Fe_{tot} ratio estimation among the analyzed samples (see Table 4 and text for discussion).

IMPLICATIONS

Here, we presented an improved Raman spectra database (after Di Genova et al. 2015) including silica-alkali-rich and iron-rich basaltic glasses together with two linear mixing models to estimate the iron oxidation state (Fe^{3+}/Fe_{tot}) from the spectra. This study, in addition to the results presented by Di Genova et al. (2015), provides a high spatial resolution (~1 μm) tool for detailed studies of the chemical composition and iron oxidation state of glasses. The implications and applications of such a tool are multiple: high spatial resolution tool for estimating chemical composition and iron oxidation state of glasses (from melt inclusions to glass matrix of rocks); in situ and remotely controlled identification, discrimination, and analyses of glasses (determination of chemical composition and iron oxidation state); and planetary science studies (e.g., Mars).

The method presented here is of particular interest for analyses of small quantities of glass such as melt inclusions and glass matrix of crystalline rocks. Indeed, the chemical composition and Fe^{3+}/Fe_{tot} ratio of melt inclusion is widely used as a chemical indicator of the melt redox conditions during the formation of magmas at depth, both on Earth and other planets. For example, Berry et al. (2008) used XANES to study the iron oxidation state of melt inclusion in komatiite to infer the condition of the Archean mantle.

As documented since the first Apollo missions, amorphous materials, especially iron-rich basaltic, are encountered frequently on the Moon (Shearer et al. 1990). Similarly, several recent studies (Horgan and Bell 2012; Blake et al. 2013; Vaniman et al. 2013; Bish et al. 2014; Downs and MSL Science Team 2015; Grotzinger et al. 2015; Kah and MSL Science Team 2015; Newsom et al. 2015) observed high abundances of alkali-silica-rich amorphous materials in sediment on Mars and martian meteorites.

Herd et al. (2001, 2002) investigated the oxygen fugacity of martian basaltic meteorites. Both studies claim that the oxygen fugacity of the samples varies by 2 log units suggesting that water may play a significant role in the oxidation of basaltic magmas on Mars or, alternatively, a secondary assimilation of ferric-iron-rich material. Our method would allow similar analyses in a much faster and cheaper way than XANES spectroscopy and, importantly, directly in situ and remotely controlled.

The potential of this methodology has recently been demonstrated by Raman apparatus, which were used to perform analyses under extreme conditions (Tarcea et al. 2008; Di Genova et al. 2015 and reference therein). Moreover, both the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) have established two forthcoming Mars mission [ExoMars program (2016–2018) and Mars 2020], using rovers equipped with Raman spectrometers, to investigate the martian environment to provide information about the potential generation of life and igneous processes on the planet. In this context, in Figure 1 we report a compilation of the chemical analyses recently performed on Mars. Inspection of the diagram reveals that the chemical compositions of the samples used in this work well match the in situ estimated chemical compositions on Mars and, for this reason, we believe that our tool will enhance the interpretive capabilities of the forthcoming Mars missions.

Another applications of our results are the possibility to discriminate the impact vs. volcanic origin of glasses. Indeed, Lukanin and Kadik (2007) presented a review of the available data on the Fe^{3+}/Fe_{tot} ratio of tektites and impact glasses, concluding that these glasses are more reduced compared with the precursor target material probably related to the characteristics of oxygen, and temperature, regime during the decompression stage following shock compression.

For all these reasons, our study extends the potential use of Raman spectroscopy to a powerful tool able to shed new light on the formation of impact craters and the type of magmatism and volcanic activity in our Solar System.

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