Clays and Clay Minerals, Vol. 63, No. 1, 15–29, 2015.

REVISITING THE INFRARED SPECTRUM OF THE WATER–SMECTITE INTERFACE

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Abstract—An overlap of bands produced by the O–H stretching vibrations of H_2O (O–H_w) and structural OH (O–H_s) in smectite hampers the study by infrared spectroscopy (IR) of both their layer and interlayer structure. The present study re-evaluated the D_2O saturation of smectite as a tool to enable separation of the overlapping bands at ambient conditions. Real-time monitoring by Attenuated Total Reflectance infrared spectroscopy (ATR-IR) was employed during *in situ* sample drying and H_2O or D_2O saturation at ambient temperature. Six dioctahedral and one trioctahedral pure smectites in Ca^{2+}-, Na^{+}-, and Cs^{+}-cationic forms were studied to explore variability in total layer charge, charge location, and interlayer cation. The IR data showed the interlayer O–D_w signature at 2700–2200 cm^{-1} as a proxy for the O–H_w signature in the 3700–3000 cm^{-1} region. In addition to the expected liquid-like bands of D_2O in the interlayer, these O–D_w spectra exhibited an additional sharp stretching feature in the 2695–2680 cm^{-1} range. No significant cation dependence of the sharp band position was observed between pairs of Ca- and Na-smectites for relative humidity (RH) between 60 and 80%, despite the large difference in the ionic potential between these interlayer cations. The intensity of the sharp band was found to be almost insensitive to changes in water content within the range 60–80% RH. The sharp band frequency decreased linearly with increasing total charge of the 2:1 layer (and can be used as a proxy for it), but no effect of charge location could be discerned. In agreement with early studies, this band was attributed to D_2O located on the surface of the interlayer, pointing one O–D group toward the siloxane surface. Based on its high frequency, this band was indicative of free O–D oscillators, with very little or no involvement in hydrogen bonding ("dangling OD"). By analogy to the spectra of D_2O-smectites, the spectrum of H_2O-smectites also involves a sharp O–H_w analog at ~3630 cm^{-1} overlapping with typical OH_s bands (*e.g.* Al_2OH). As a result of this overlap, the sharp 3630 cm^{-1} O–H_w contribution was often missed or attributed solely to O–H_s.

Key Words—Adsorbed Water, ATR, Deuteration, Infrared Spectroscopy, Layer Charge, Smectite.

INTRODUCTION

Analysis of the mid-IR spectra of clay minerals is often hampered by the overlap of bands originating from structural OH groups (OH_s) and OH groups of adsorbed water (OH_w) in the O–H stretching region (3700–3000 cm^{-1}). Unambiguous distinction between the different types of O–H_s and O–H_w stretching modes of clay mineral samples is a crucial prerequisite for their further systematic investigation by IR. This is especially true in the case of dioctahedral smectites. The lack of distinction between O–H_s and O–H_w in the 3640–3610 cm^{-1} range impedes both the study of interlayer H_2O and the identification of individual O–H_s stretching components, and hence, also, the establishment of correlations between O–H_s stretching and the octahedral-sheet composition (*e.g.* Madejová *et al.*, 1994; Fialips *et al.*, 2002; Petit *et al.*, 2002; Zviagina *et al.*, 2004).

Following the seminal work of V.C. Farmer and his group at the Macaulay Institute, Aberdeen, UK, a number of monographs and review papers have dealt in depth with the application of IR to the identification and structural characterization of clay minerals, raising the issue mentioned above (Farmer, 1974; Russell and Fraser, 1994; Petit *et al.*, 1995; Besson and Drits, 1997; Madejová and Komadel, 2001; Madejová, 2003; Gates, 2005). Early IR research was based mostly on thin self-supported clay films measured in transmission using dispersive instruments fitted with suitable environmental cells. More recent studies have benefited from the advent of Fourier transform spectrometers and Attenuated Total Reflectance (ATR) collection optics offering improved spectral quality, convenient non-invasive spectral acquisition, and new possibilities for real-time monitoring (*e.g.* Johnston *et al.*, 1992; Yan *et al.*, 1996; Ras *et al.*, 2007).

Despite the widespread application of IR to clays and clay-based materials, it appears that some of the early pioneering work is fading out without being followed or challenged by modern findings. Early IR work based on substituting interlayer H_2O with D_2O provided evidence that the sharp, high-frequency bands observed at

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DOI: 10.1346/CCMN.2015.0630102

https://doi.org/10.1346/CCMN.2015.0630102 Published online by Cambridge University Press

~3640–3610 cm^{-1} involve a significant contribution from weakly hydrogen-bonded (H-bonded) adsorbed $O-H_w$ (Russell and Farmer, 1964; Farmer and Russell, 1971; Suquet *et al.*, 1977; Sposito and Prost, 1982; Cariati *et al.*, 1981, 1983; Sposito *et al.*, 1983). More recent assignments of the same high-frequency feature in dioctahedral smectites vary. Some authors adopt the aforementioned assignment of an $O-H_w$ stretching mode (*e.g.* Bishop *et al.*, 1994; Madejová *et al.* 1994) and others assign it only to $O-H_s$, and not $O-H_w$ (Bukka *et al.*, 1992; Xu *et al.*, 2000; Madejová and Komadel 2001).

Substitution of interlayer H_2O with D_2O seemed to offer an elegant solution to the problems described above, as D_2O band positions are shifted by a factor of ~1.36 toward lower wavenumbers. The effectiveness of this technique seemed to be confirmed (Farmer and Russell 1971); D_2O saturation can be considered as useful provided that no deuteration of OH_s is assured. Russell *et al.* (1970) studied *in situ* deuteration of structural OH in a number of smectites. Relatively high temperatures and long reaction times (300–400ºC, 1–14 h) were needed for the complete H/D exchange of the structural OH. The progress of OH_s deuteration was manifested by the growing intensity of the structural δ OD bending modes: Al_2OD was observed at 700–690 cm^{-1}, AlFe(III)OD at ~675 cm^{-1}, and AlMgOD at ~650 cm^{-1} (compared to the corresponding δ OH modes at ~915, 880, and 840 cm^{-1}, respectively). The appearance of these bands in spectra of smectites after saturation with D_2O can be treated as an indicator of OH_s deuteration. Some effects interpreted as partial deuteration of OH_s were, however, observed at lower temperatures (98ºC, Bukka *et al.*, 1992).

The aim of the present study was to re-evaluate D_2O saturation as a convenient spectrochemical tool for the separation of the $O-H_s$ and $O-H_w$ ($O-D_w$) stretching modes of smectite at ambient hydration conditions. Seven smectite samples in three cation-exchanged forms were selected to represent most of the variability found in nature. The spectrum of water (as D_2O) was obtained free from the interference of structural OH groups and analyzed in terms of layer charge, charge location, and exchangeable cation.

EXPERIMENTAL

Materials

The present study was based on six natural dioctahedral smectites from the collection of the Source Clays Repository of The Clay Minerals Society and one synthetic saponite (Table 1). SCa-3 and SAz-2 are high-charge montmorillonites with almost no tetrahedral charge. SWy-2 (Wyoming) is a low-charge beidellitic montmorillonite. SWa-1 is a low-charge Fe-rich smectite/nontronite with almost equal amounts of tetrahedral and octahedral charge. SbCa-1 and SbId-1 are beidellites with high and low charges, respectively. The synthetic saponite (SAP) is a high-charge member of the trioctahedral series reported by Pelletier *et al.* (2003).

All dioctahedral smectite samples were purified by removing carbonates, organics, and Fe-oxides/hydroxides (except SWa-1) by a sequence of acetic acetate buffer, peroxide, and buffered sodium dithionite treatments (Jackson, 1969). Subsequently, particle-size fractions were separated by centrifugation and dialyzed in deionized water. All fine fractions were found to be mineralogically pure, with the exception of SbId-1 which contained a kaolinite admixture, clearly evident in the IR spectra. Homoionic forms of each smectite were prepared by five washings with appropriate 0.5 M Ca^{2+}, Na^+, and Cs^+ chloride solutions of reagent-grade purity and dialysis in deionized water.

The literature on smectite samples from the Source Clays Repository reports various size fractions with different mineral formulae and layer-charge density (*e.g.* Zviagina *et al.*, 2004; Gates, 2005). Moreover, the determination of the total exchangeable cations as a way to measure layer-charge density is method-dependent (Wolters *et al.*, 2009) and literature values may not be comparable to each other unless determined by the same method. For these reasons, the total layer charge per half unit cell (Q_{tot}) of the actual particle fractions used in the study was determined independently (Table 1). This charge determination was based on the measurement of the Na content in the Na-exchanged samples subjected to conventional acid digestion, using a flame photometer (Sherwood 420 by Sherwood Scientific Ltd., Cambridge, UK) calibrated against NIST standards 76a and 70a.

Table 1. Smectites used in the study.

Sample	Layer type	Charge location	Particle size fraction	Total layer charge Q_{tot}
SCa-3	montmorillonite	octahedral	<1.0 μm	0.51(1)
SAz-2	montmorillonite	octahedral	<2.0 μm	0.52(1)
SWy-2	montmorillonite	octahedral/tetrahedral	<0.1 μm	0.36(1)
SWa-1	nontronite	tetrahedral/octahedral	<1 μm	0.31(1)
SbCa-1	beidellite	tetrahedral	<1.0 μm	0.50(1)
SbId-1	beidellite	tetrahedral	<0.1 μm	0.39(1)
Saponite	saponite, trioctahedral	tetrahedral	<2 μm	0.58(1)

https://doi.org/10.1346/CCMN.2015.0630102 Published online by Cambridge University Press

Estimates of the molecular weights for each smectite were based on literature compositions.

ATR-IR experiments

Infrared spectra (4000−580 cm^{-1}) were collected on two Fourier transform instruments (Equinox 55 by Bruker Optics and Nicolet 6700 by Thermo Scientific) equipped with single-reflection diamond ATR accessories (DuraSampl IR II by SensIR Technologies and high-temperature Golden Gate by Thermo Scientific, respectively). The spectra were measured as 100-scan averages with 4 cm^{-1} resolution ($\Delta\nu$ = 2 cm^{-1} by interferogram zerofill) and reported after correction for the dependence of the penetration depth on wavelength. Second derivatives were calculated with Savitzky-Golay routines.

Spectra were measured from ~5−10 μm-thick films. The films were made by careful depositing and drying of a few drops of an aqueous sonicated suspension of smectite on the top of the ATR crystal, avoiding air bubbles or voids that could reduce contact between the thin film and the ATR crystal surface. The ATR plate was fitted with a home-made purging cap which enabled IR monitoring during purge drying or vapor hydration at ambient temperature (25±1ºC). The as-prepared smectite films were subjected to one of the following treatments:

(a) Equilibration under a N_2 flow with adjustable relative humidity (RH = 19−90±2%) of H_2O or D_2O vapor, which was produced by a humidity generator (HG-100 by L&C Science and Technology, Hialeah, Florida, USA). At each stepwise stabilized RH value, two spectra were collected after ~5 and ~10 min to ensure sample equilibration with the vapor.

(b) Alternating D_2O/HDO/H_2O wetting and N_2 purge-drying cycles as in Bukas *et al*. (2013). During each cycle, equilibration for at least 15 min was performed in order to achieve complete substitution.

N_2 of purity 5.0 and D_2O with 99.9%$_{at}$, D/H (Sigma-Aldrich) were used in both cases. A systematic study of hydration/dehydration kinetics (*cf.* Fu *et al.*, 1990) was not performed and the quantitative determination of H_2O/D_2O in the smectite samples is beyond the scope of this paper.

RESULTS AND DISCUSSION

Smectites saturated with H_2O at different RH conditions

The dependence of the ATR-IR spectra of Ca- and Na-SWy-2 exposed to variable RH (19−90% at 25ºC, Figure 1) is typical for montmorillonite and analogous trends have been reported in numerous previous publications (*e.g.* Xu *et al.*, 2000; Madejová *et al.*, 2002; Madejová, 2003 and references therein). Briefly, IR activity is observed in three frequency ranges: ~3700−3000 cm^{-1} (ν O−H_s, O−H_w), 1650−1600 cm^{-1} (δ H_2O), and ~1200−800 cm^{-1} (dominated by various strong Si−O modes). The bending modes of the structural OH groups (δ OH_s) are superimposed on the low-frequency side of the strong Si−O envelope and are diagnostic of the octahedral layer substitutions. In the spectrum of SWy-2 these bending modes are observed at ~915, 881, and 843 cm^{-1} and attributed to Al_2OH, AlFe(III)OH, and AlMgOH pairs, respectively (*e.g.* Madejová *et al.*, 2002; Madejová, 2003; Gates, 2005 and references therein). In contrast to the bending modes, the corresponding O−H_s stretching component bands of the three dioctahedral species are not easily resolved (Zviagina *et al.*, 2004 and references therein). These OH_s bands contribute collectively to the band at 3625 cm^{-1} (Figure 1), which appears to be rather insensitive to both the hydration state and the interlayer cation.

The effect of progressively decreasing RH on the spectrum of montmorillonite is largely manifested by the decrease in intensity and slight shift to higher frequencies of the broad peaks at ~3400 cm^{-1}. The exact position of this peak is cation dependent (3392 cm^{-1} in Ca-SWy-2 and 3405 cm^{-1} in Na-SWy-2, Figure 1). A less pronounced decrease in intensity of the band at ~1630 cm^{-1} and a concomitant shift to lower frequencies upon drying are observed, in agreement with previous literature (Johnston *et al.*, 1992; Madejová *et al.*, 2002; Madejová, 2003; Gates, 2005). Clearly, the features at ~3400 and ~1630 cm^{-1} ought to be attributed to H_2O on the basis of their response to drying and their dependence on the interlayer cation. A weak shoulder at ~3215 cm^{-1} is also ubiquitous in the spectra of smectites (Figure 1). An early assignment of this feature to the overtone of the H_2O bending (~1630 cm^{-1}) by Farmer (1974) has been adopted in the recent literature. Perhaps a more appropriate description would consider the ~3400 and 3215 cm^{-1} bands of H_2O as resulting from the Fermi resonance between the stretching fundamental and the bending overtone of H_2O (Efimov and Naberukhin, 2002; Sovago *et al.*, 2009). Some smectites are reported to exhibit an additional poorly resolved band at 3580−3540 cm^{-1}, also attributed to O−H_w stretching (Bishop *et al.*, 1994; Xu *et al.*, 2000; Madejová *et al.*, 2002) and not to O−H_s (*e.g.* Zviagina *et al.*, 2004). All typical H_2O-related features and trends upon drying were observed for all smectites in this study. Comparing the Ca- and Na-forms of the SCa-3 montmorillonite and the SbCa-1 beidellite (Figure 2) with those of SWy-2 (Figure 1) indicated that each smectite responds to changing %RH by adjusting the intensity of the broad band at ~3400 cm^{-1}, whereas the high-frequency sharp O−H stretching component is relatively unaffected. The position of the ~3400 cm^{-1} band appeared to depend more on the type of interlayer cation and less on the type of 2:1 layer. The ~3400 cm^{-1} band shifted to higher frequencies upon drying and this effect was more pronounced in the Na- than in the Ca-smectites (Figure 3a). This is mostly because, for any given value of %RH, the H_2O content of smectites is strongly dependent on the nature of the interlayer cation.

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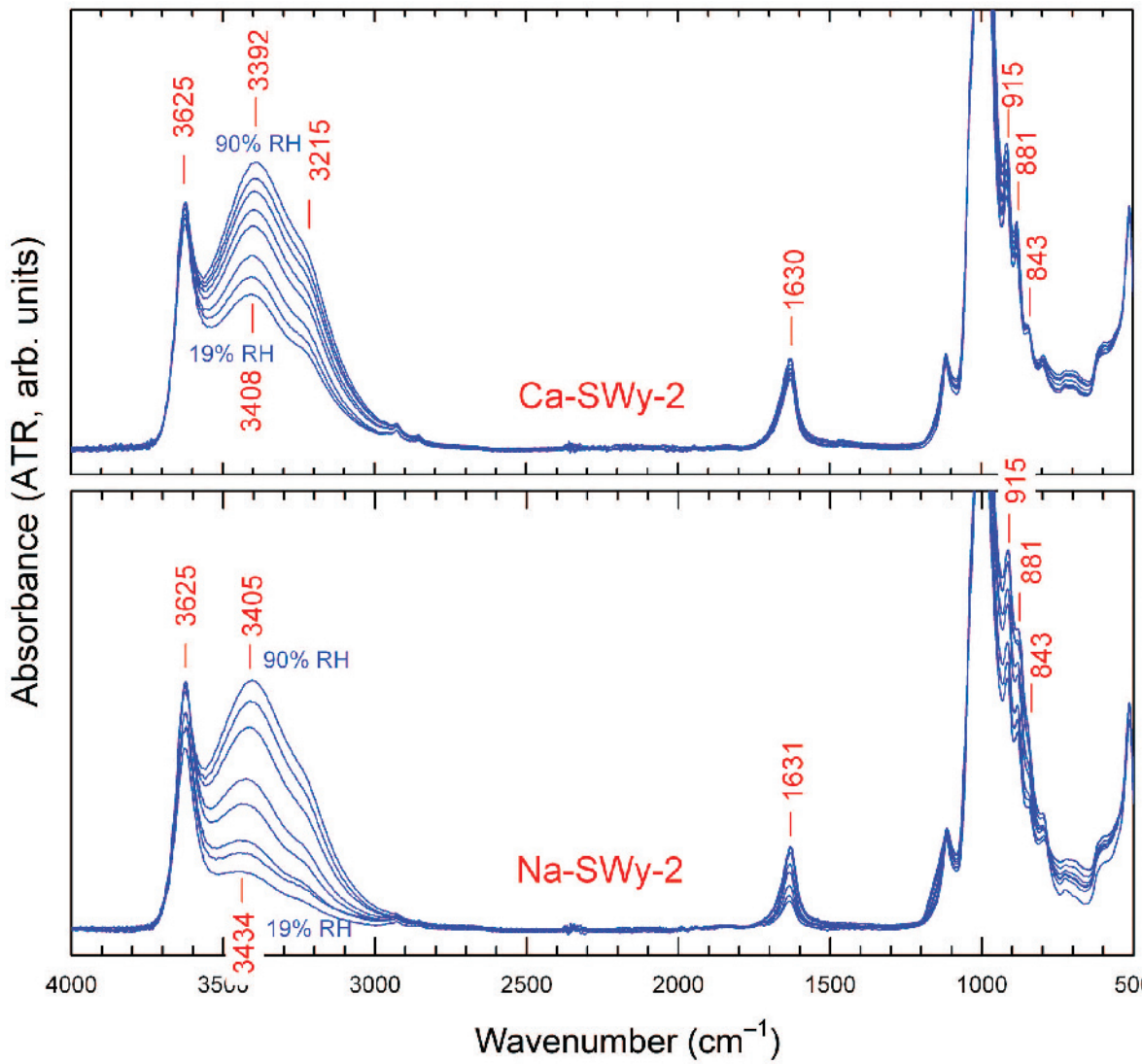


Figure 1. ATR-IR spectra of Ca- (upper) and Na-SWy-2 montmorillonite (lower) as a function of relative humidity (19−90%) at 25ºC.

According to Chiou and Rutherford (1997), Ca-SWy-1 equilibrated at 90% RH has ~250 mg of H_2O/g clay whereas the corresponding content in Na-SWy-1 is ~190 mg H_2O/g. Similarly, at 19% RH the H_2O contents are ~90 mg of H_2O/g in Ca-SWy-1 and 15 mg of H_2O/g in Na-SWy-1 corresponding to 10.4 and 0.9 H_2O molecules per exchangeable cation, respectively. These trends in H_2O content *vs.* %RH were in qualitative agreement not only with the varying intensity of the 3500−3000 cm^{-1} envelope (Figures 1 and 2) but also with its varying position (Figure 3b), in agreement with Xu *et al.* (2000) and Madejová *et al.* (2002). In contrast, changes in the water content appeared not to affect the position, intensity, and shape of the ~3625 cm^{-1} band, which was least sensitive to the interlayer cation type and hydration stage in the range of water content studied (Figures 1 and 2). As shown by Madejová *et al.* (1994) and Zviagina *et al.* (2004), the exact position (3633 cm^{-1} in SbCa-1, 3625 cm^{-1} in SWy-2, and 3616 cm^{-1} in SCa-3 in both the Ca- and Na-series) and the shape of the ~3625 cm^{-1} band in the three smectites are related to their different octahedral-sheet compositions.

Based on the information above, the response of the smectite IR spectra to varying hydration appears to be consistent with the assignments of the ~3625 cm^{-1} and ~3400 cm^{-1} bands to O−H$_s$ (structural) and O−H$_w$ (water), respectively, in agreement with many recent studies (Xu *et al.*, 2000; Madejová and Komadel, 2001; Madejová *et al.*, 2002; Madejová, 2003). Does this simple interpretation withstand a D_2O saturation test? D_2O saturation is expected to move the entire set of H_2O bands to lower frequencies, replacing the δ H_2O at ~1630 cm^{-1}, its overtone at ~3215 cm^{-1}, and the

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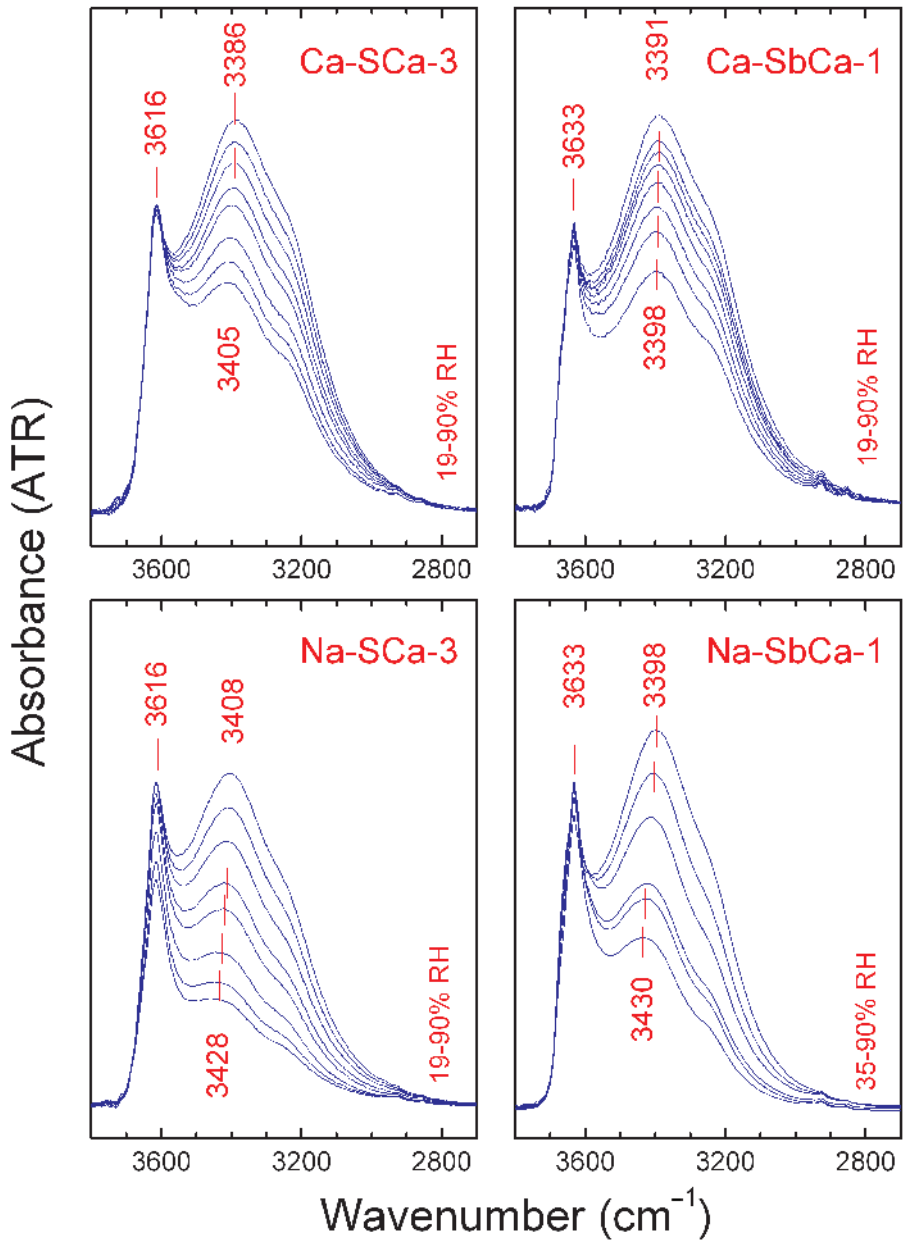


Figure 2. Details of the ATR-IR spectra of Ca- and NaSCa-3 montmorillonite and high-charge beidellite (SbCa-1) as a function of relative humidity at 25ºC.

ν O–H_w at ~3400 cm^{-1} with their corresponding D_2O bands at ~1200, ~2370, and ~2500 cm^{-1}, respectively (ν (H/D) ≈ 1.36). If the three aforementioned H_2O bands are the only ones that originate from water adsorbed on the smectite surface, no new bands other than their D_2O analogs should be observed upon D_2O saturation.

D_2O- vs. H_2O-saturated samples

Cycling D_2O vapors and dry N_2 at ambient conditions over oriented smectite film resulted in an almost complete saturation with D_2O, as indicated by the comparison of the ATR-IR spectra of the H_2O- and D_2O-forms of Na-SWy-2 (Figure 4), collected at ~50% RH (*cf.* Figure 3). The 1200–800 cm^{-1} range of a smectite spectrum undergoes systematic changes in peak positions and intensities upon varying %RH (in agreement with Yan *et al.*, 1996), regardless of whether the sample is saturated with D_2O or H_2O. Appropriate comparison of data collected during different experiments (*e.g.* Figure 4) required, therefore, that the spectra be matched based on the same or very similar hydration states.

Saturation with D_2O resulted in a significant decrease in absorbance at 3800–3000 cm^{-1} (due to O–H_w stretching)

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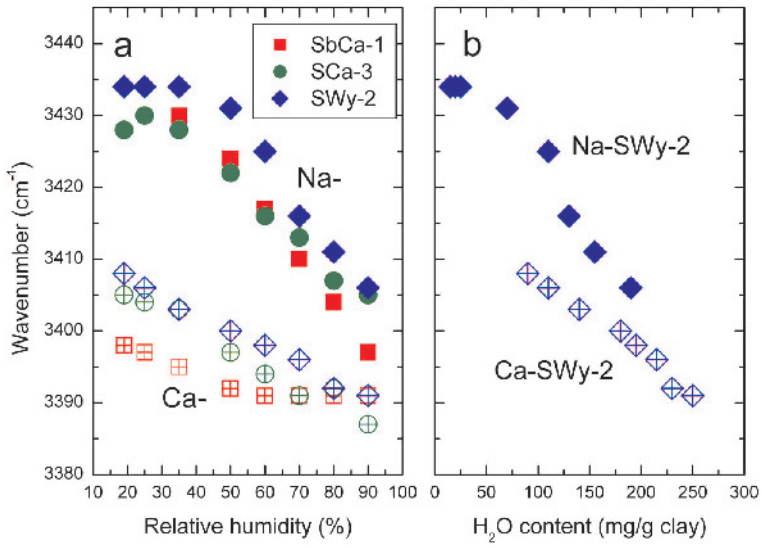


Figure 3. (a) Dependence of the position of the H_2O stretching mode at ~3400 cm^{-1} on relative humidity for the clays shown in Figures 1 and 2. (b) The same frequency data for SWy-2 plotted *vs.* the corresponding H_2O contents of Chiou and Rutherford (1997).

and the appearance of a new complex band envelope of O–D stretching at 2800–2200 cm^{-1}. A sharp, asymmetric O–H band peaking at 3624 cm^{-1} persisted during D_2O saturation at ambient conditions. A spectral difference profile between D_2O- and H_2O-saturated forms of Na-SWy-2 (Figure 4) is close in shape to the O–D profile, but the positions of bands are shifted by ν (H/D) = 1.36. Furthermore, the bending mode of D_2O was observed at ~1205 cm^{-1}, no H_2O bending was observed at ~1630 cm^{-1}, and the very low-intensity band at ~1450 cm^{-1} indicated that there was no significant contribution from HDO molecules. The 2δ D_2O Fermi-resonant overtone was also noticeable at 2374 cm^{-1}, as anticipated.

The as-produced O–D stretching profile of D_2O-saturated Na-SWy-2 exhibited the expected broad features of liquid D_2O peaking at ~2500 cm^{-1} (Bertie *et al.*, 1989), but involved an additional sharp feature observed at 2686 cm^{-1} in the absorbance mode, which was better resolved at 2692 cm^{-1} in the 2nd derivative mode (Figure 4). The corresponding O–H position was 3638 cm^{-1} (H/D = 1.35), as determined from the 2nd derivative of the H_2O–D_2O difference spectrum.

The origin of the sharp 2692 (3638) cm^{-1} O–D (O–H) band needs to be clarified. A close inspection of both absorbance and the 2nd derivative spectra of H_2O- and D_2O-wet Na-SWy-2 (Figure 4) indicated that the intensity of the δ OH bands (at 913, 878, and 841 cm^{-1}, respectively) did not decrease upon D_2O wetting and no features attributable to δ OD_s were observed. Hence, the D_2O saturation under the conditions employed did not produce OD_s detectable by IR. As a consequence, the sharp 2692 (3638) cm^{-1} band ought to be associated with OD_w (OH_w). The presence of this sharp high-frequency D_2O band, which is absent from the spectra of liquid D_2O (Max and Chapados, 2009), is ubiquitous in the spectra of all smectites and in all cationic forms investigated here. Several representative examples (Figure 5) demonstrate that the 3800–2800 cm^{-1} spectral difference between the H_2O- and D_2O-saturated samples matches in all cases the 2800–2100 cm^{-1} O–D stretching envelope of D_2O. In most H_2O-wet samples, the frequency range between 3650 and 3615 cm^{-1} involves unresolved contributions from both O–H_w and O–H_s. Exceptions are saponite and nontronite which exhibit O–H_s modes at higher and lower frequencies, respectively (Mg_3OH: ~3683 cm^{-1}, $Fe(III)_2OH$: ~3560 cm^{-1}). Incidentally, the fact that D_2O-wet saponite and nontronite both exhibit a high-frequency D_2O stretching peak differing by <30 cm^{-1} (Figure 5) whereas their structural OH_s peaks are >120 cm^{-1} apart adds further support to the assignment of the high-frequency O–D stretching to O–D_w and not to O–D_s.

Further evidence supporting the assignment of the sharp 2692 (3638) cm^{-1} band to O–D_w (O–H_w) comes from the near-IR spectra of smectites, which allow for the full separation of OH_w from OH_s by means of the (ν+δ) stretching-bending combination modes, due to large separation between the combination modes of smectite structure (ν O–H_s ~3620 cm^{-1}, δ OH_s ~916 m^{-1} and below that results in (ν+δ) at ~4536 cm^{-1}) and water (ν O–H_w ⩾3610 m^{-1}, δ H_2O at ~1635 m^{-1} which results in (ν+δ) at ~5250 cm^{-1}) (Bishop *et al.*, 1994; Cariati *et al.*, 1981). Montmorillonite clays exhibit a sharp H_2O (ν+δ) combination mode at ~5250 cm^{-1} (Clark *et al.*, 1990; Bishop *et al.*, 1994). As the position of δ (H_2O) is always at ~1630 cm^{-1}, analogous to δ (D_2O) at ~1205 cm^{-1} (Table 2), the (ν+δ) combination band cannot possibly involve the stretching at ~3420 cm^{-1} and requires the presence of a ν (O–H_w) mode with a position greater than 3610 cm^{-1} (Cariati *et al.*, 1981).

Based on the above, the sharp band at 2680–2694 cm^{-1}, which is observed in all D_2O-wet

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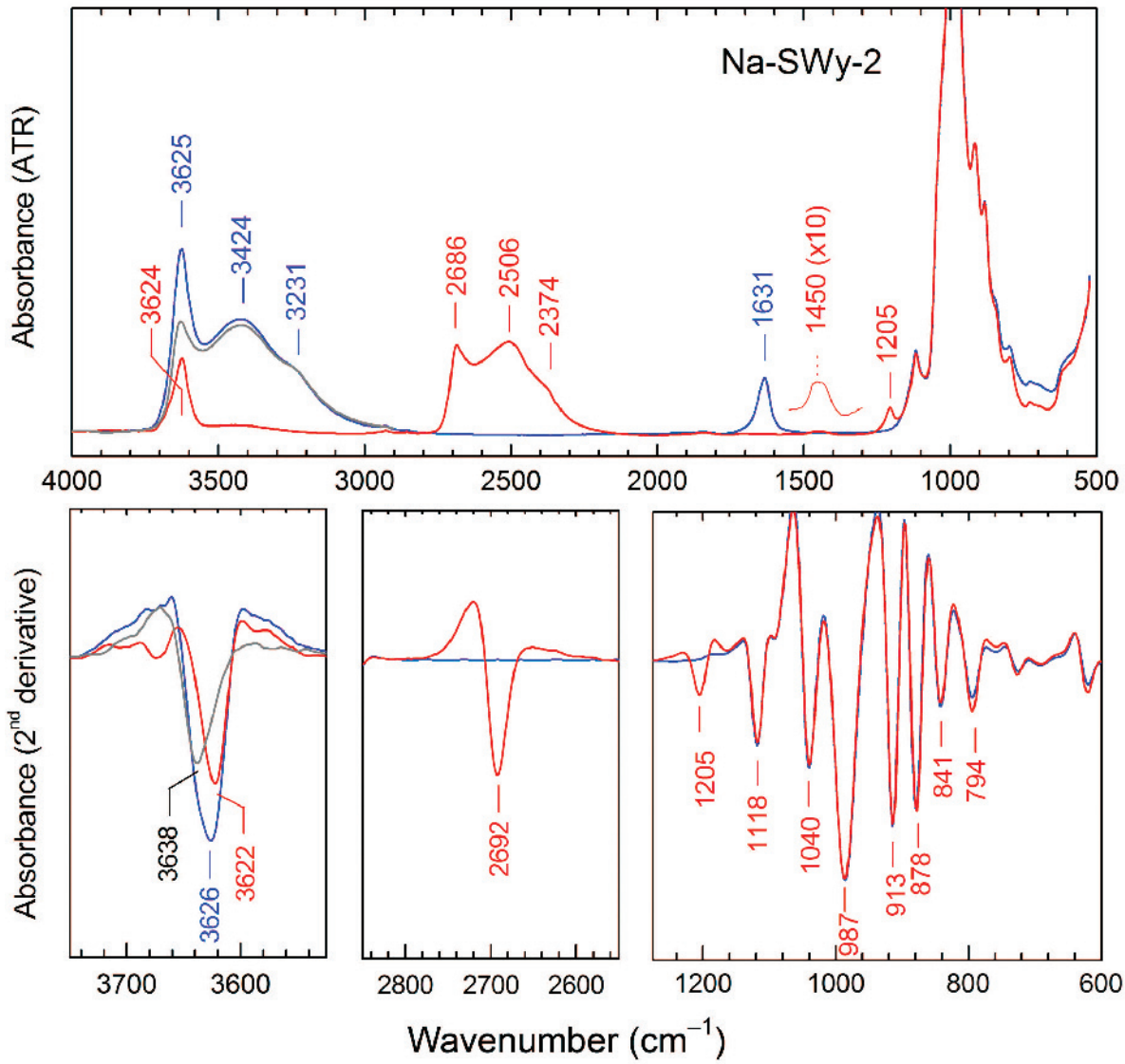


Figure 4. (Upper) Comparison of the ATR-IR spectra of Na-SWy-2 montmorillonite equilibrated by H_2O (blue) and D_2O (red) at ~50% relative humidity, 25ºC. Their difference spectrum in the 4000–2800 cm^{-1} range is included (gray). The very weak absorbance intensity at ~1450 cm^{-1} indicates that only trace HDO is present in the D_2O sample. (Lower) Details of the 2nd derivative ATR-IR and difference spectra over selected wavenumber ranges.

Table 2. Positions (cm^{-1}) of the high-energy O–D stretching component, ν (O–D), and bending δ (D_2O) bands for D_2O-saturated samples at ambient conditions and in different cationic forms. Band positions were determined from the minima of 2nd derivatives with 13-point Savitzky Golay smoothing.

Sample name	ν (O–D)			δ (D_2O)		
	Ca	Na	Cs	Ca	Na	Cs
SWa-1	2692.1(5)	2692.8(5)	2691.4(1)	1202.3(5)	1202.6(5)	1203.8(5)
SWy-2	2691.7(5)	2692.1(5)	2693.2(5)	1201.9(5)	1203.6(5)	1207.1(5)
SbId-1	2689.3(5)	2689.4(5)	2691.6(5)	1203.8(5)	1205.0(5)	1207.6(5)
SbCa-1	2685.5(5)	2684.5(5)	n.a.	1204.9(5)	1207.4(5)	n.a.
SCa-3	2686.2(5)	2685.5(5)	2689.4(5)	1202.4(5)	1204.9(5)	1206.5(5)
SAz-2	2686.0(5)	2686.1(5)	2690.0(5)	1202.4(5)	1204.9(5)	1206.2(5)
SAP	2684(2)	2682(2)	2687(2)	1204.4(5)	1205.5(5)	1205.0(5)

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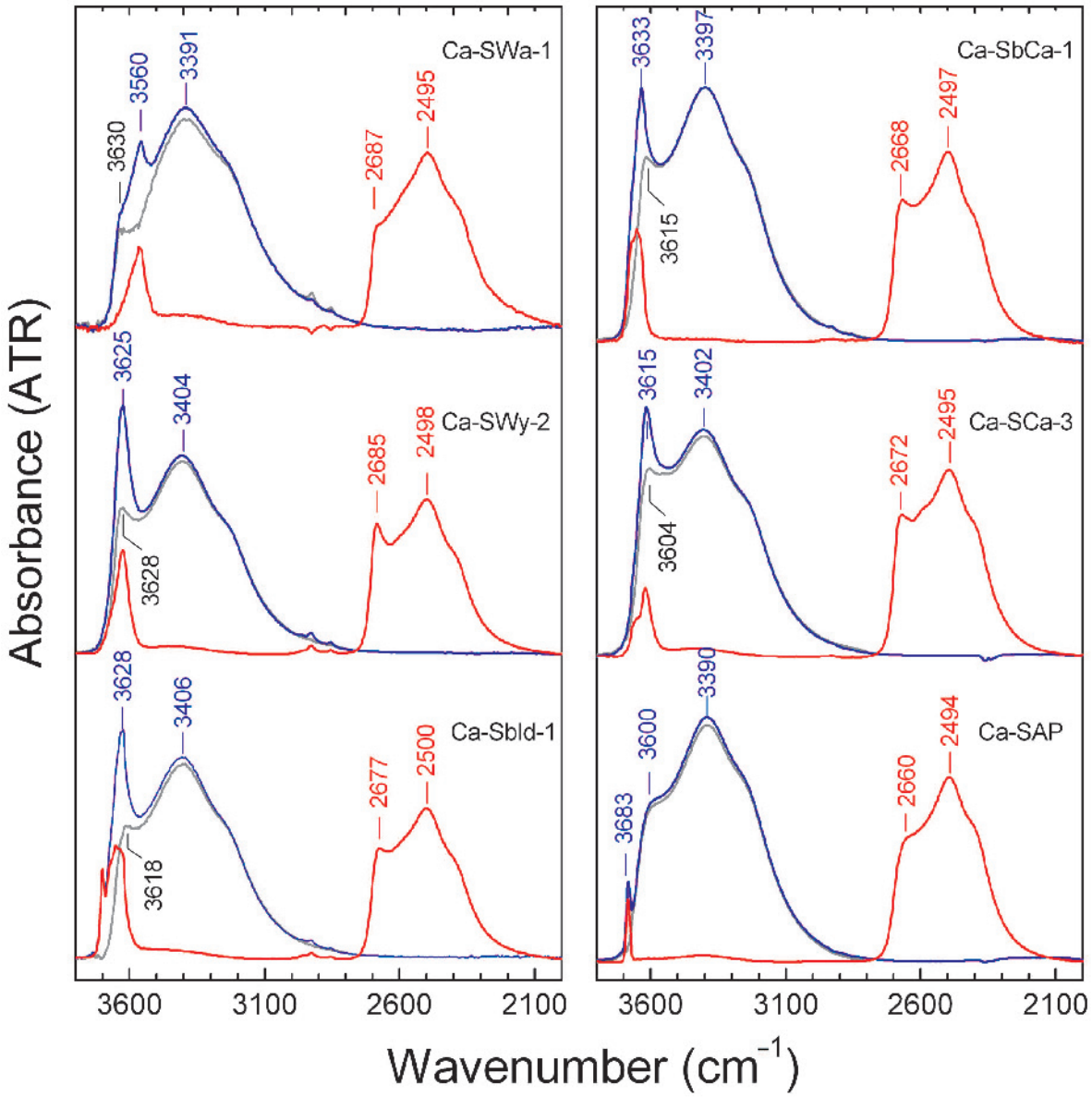


Figure 5. Absorbance spectra of smectites equilibrated with ~50% RH of H_2O (blue) or D_2O-vapor (red) and their difference in the O−H stretching range (gray). The spectra of the SAz-2 montmorillonite (SAz-2, not shown) are nearly identical to those of the SCa-3 sample. All samples are in Ca-form.

smectites, must be produced by a D_2O stretching mode and not by deuterated structural hydroxyls. In H_2O-wet samples, this band has an analog at 3638 cm^{-1} which cannot be resolved easily from the stretching modes of the structural hydroxyl groups (O−H_s) peaking at ~3622 cm^{-1} (Figure 4).

Smectites saturated with D_2O at different RH conditions

In the O−D stretching region, the intensity of a band at ~2500 cm^{-1} increased with increasing %RH, as shown for a representative sample SWy-2 (Figure 6), irrespective of interlayer cation type. This trend is similar to the evolution of the OH_w stretching envelope (*cf.* Figures 1 and 6). The sharp band at ~2686 cm^{-1} is always present in the spectra, irrespective of %RH, with a relatively uniform intensity for the Ca-form, except at the lowest %RH values. The number of D_2O molecules responsible for the sharp band must thus remain relatively constant throughout the experiment, whereas the number of molecules in the non-interface position in the interlayer (cation-bound, bulk water) decreases with decreasing RH, causing a significant intensity decrease below 2600 cm^{-1} (*cf.* Johnston *et al.*, 1992; Xu *et al.*, 2000). The same trend is visible for Na-SWy-2 although changes in the position and intensity of the sharp band are more pronounced and start at higher RH (Figure 6).

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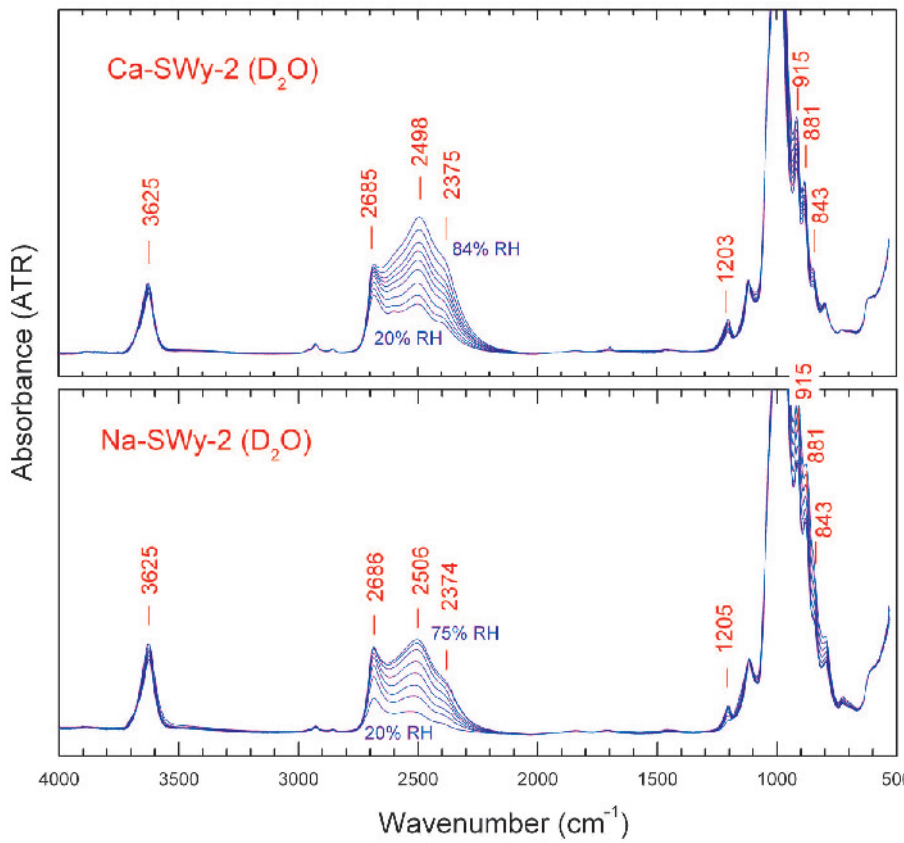


Figure 6. ATR-IR spectra of D_2O-exchanged, Ca- (upper) and Na-SWy-2 montmorillonite (lower) equilibrated at variable D_2O relative humidity at 25ºC.

The lack of structural O–D_s bending bands at frequencies observed by Russell *et al.* (1970) proves that, within the detection limits of ATR-IR, no deuteration of structural OH groups occurred.

Changes of the sharp band position as a function of changing RH were traced with a 2nd derivative approach for samples SWy-2 and SCa-3 in Na- and Ca-forms (Figure 7). The sharp band is at higher frequency for SWy-2 in both cationic forms than for the SCa-3 sample and is relatively constant for RH between 60 and 80%. At lower RH, the frequency of the sharp band decreases. The band position for the SCa-3 sample stays relatively constant across a broad range of RH for both interlayer cations (Figure 7). The largest difference in the sharp band position between the samples is observed for RH between 60 and 80%. In all samples studied the sharp band position is very stable within that range of RH. The RH range between 60 and 80% was, therefore, chosen to

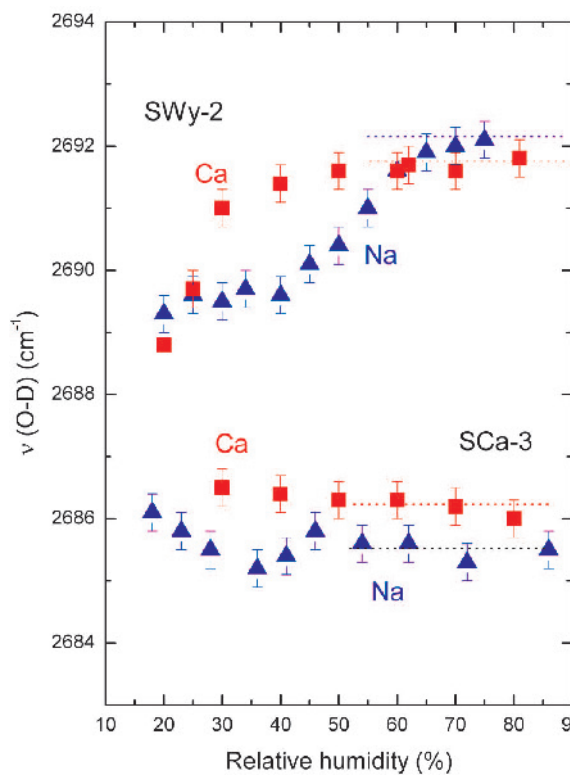


Figure 7. Positions (cm^{-1}) of the high-frequency O–D stretching component, ν (O–D), of D_2O-saturated SWy-2 and SCa-3 montmorillonite in Ca- and Na-forms as a function of D_2O relative humidity at 25ºC. Values are taken from the minima of the 2nd derivatives with 13-point Savitzky Golay smoothing. Dashed lines indicate average values included in Table 1.

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record the sharp band positions for the remaining samples, despite greater overlap with a broad O–D stretching band at ~2500 cm^{-1}.

Systematics of the high-frequency D_2O stretching band in smectites

A 2nd derivative with 13-point Savitzky-Golay filter, corresponding to a window of ±12 cm^{-1} around the central point, was employed to find the peak position of the sharp band for each smectite analyzed (Table 2). This smoothing filter was chosen to provide the maximum contrast between the sharp 2700–2670 cm^{-1} O–D stretching band and the broader 2500– and 2400 cm^{-1} component band. The 2nd derivative minima of the O–D bands were consistently found at higher energy than the apparent maxima of the corresponding absorbance spectra (*e.g.* Figure 4), which can be explained by the presence of additional poorly resolved components in the 2700–2500 cm^{-1} range that results in the shifting of the apparent absorbance maxima towards slightly lower frequency.

A linear decrease of frequency was observed upon increasing the total layer charge of the smectite (Table 2 and Figure 8). No effects of octahedral layer type (dioctahedral or trioctahedral) or charge location (tetrahedral or octahedral) on peak position were observed. In addition, little or no difference between the Ca-saturated and Na-saturated smectite series was noted. The fitted lines for Ca- and Na-saturated smectites (Figure 8) were identical within error and could be approximated by a single equation:

$$\nu\ (O–D) = 2703.9 - 35.8Q_{tot},\ (R^2 = 0.94,\ n = 14) \quad (1)$$

The Cs-saturated series showed a much weaker dependence on Q_{tot}:

$$\nu\ (O–D) = 2698 - 17Q_{tot},\ (R^2 = 0.76,\ n = 6) \quad (2)$$

HDO-saturated smectites

The stretching envelope of H_2O and D_2O is complicated by the intramolecular coupling between the two O–H or two O–D bonds. In an attempt to reduce this intramolecular coupling, some earlier studies (*e.g.* Farmer and Russell, 1971; Suquet *et al.*, 1977) reported the spectra of HDO instead of D_2O in smectites. Briefly, this type of isotopic enrichment involves wetting the samples with a mixture of D_2O:H_2O, typically 20:80 by volume (~36% HDO, 60% H_2O, and 4% D_2O), and

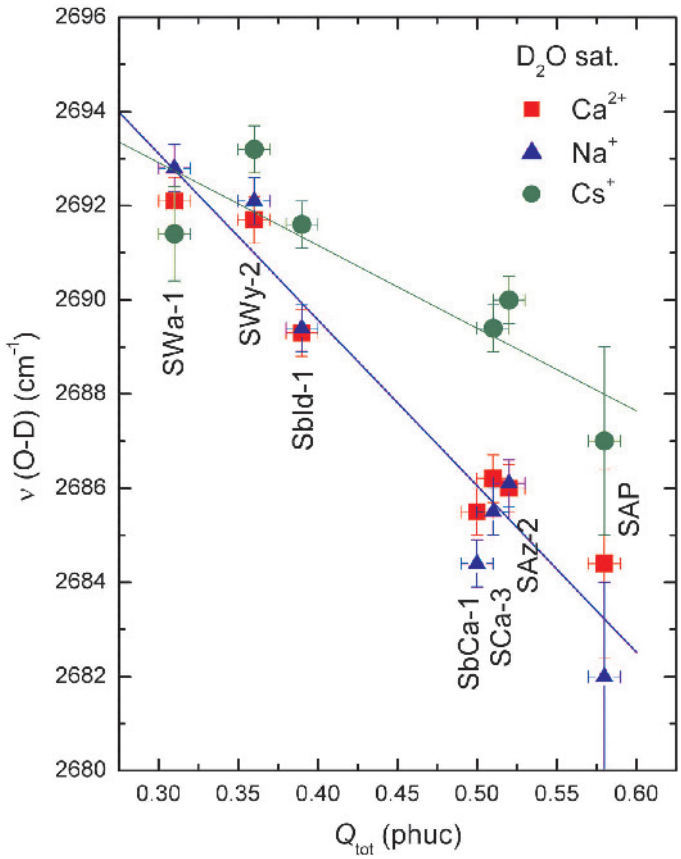


Figure 8. Dependence of the position of the sharp, high-frequency O–D stretching of D_2O-saturated smectites on total charge per half unit cell (Q_{tot}) and compensating cation (Ca^{2+}, Na^+ and Cs^+). The straight lines are least-squares fits.

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studying the spectra in the O–D stretching range (Figure 9). The HDO-saturation experiments of all seven smectites in three cation forms were performed. The sharp, high-energy OD band of HDO was observed in all samples, always at wavelengths 20–30 cm^{-1} lower than in D_2O-saturated samples, in qualitative agreement with Farmer and Russell (1971). A similar dependence on smectite charge and interlayer cation was observed as in the case of D_2O-wetting (Figure 10). In contrast, the strongly H-bonded part of the D_2O stretching domain showed an opposite shift (2506 for D_2O and 2523 cm^{-1} for HDO in the case of Na-SWy-2 – Figure 9). In addition, the ~2400 cm^{-1} component was absent from the spectra of the HDO-smectite, which is consistent with its assignment to a Fermi resonance 2δ D_2O component and simplifies the spectrum of HO–D stretching modes. On the other hand, the advantages of studying HDO- instead of D_2O-saturated smectite samples are counterbalanced by the inevitably weaker intensity of the HO–D stretching envelope, which results in a worse signal-to-noise ratio and the larger bandwidths associated with the isotope combinations in a mixed H-bonded tetrahedral $O(H,D)_4$ network (Max and Chapados, 2002).

Origin of the sharp $O–D_w/O–H_w$ band

Within the %RH range studied, the sharp, high-frequency IR band at ~2685 cm^{-1} (D_2O) or ~3630 cm^{-1} (H_2O) was a common feature for all smectites investigated, with a position and intensity showing remarkable insensitivity to interlayer cation type or interlayer water content, but with noticeable dependence on layer charge (Table 2, Figure 5). An opposite behavior was observed for the ~3400 cm^{-1} (H_2O), and ~2500 cm^{-1} (D_2O) OH_w/OD_w stretching envelopes that exhibited a strong dependence on hydration stage and interlayer cation (*cf.* Xu *et al.*, 2000; Madejová *et al.*, 2002), but were relatively unaffected by the layer charge or charge location of the smectites studied (Figure 4).

Notably, the position of the sharp band showed a negligible difference between the Na- and Ca-forms of any of the smectites studied, despite the large difference in ionic potential and hydration enthalpy between these cations. Cs^+ has the lowest hydration enthalpy among naturally occurring single, non-complex cations. Nevertheless, Cs-smectites obey a weak linear relationship between the OD sharp band position and the total layer charge of smectite although the correlation line slope is different from the Na- and Ca-forms.

The high frequency of the sharp stretching mode suggests its origin from O–H (O–D) oscillators which are involved in very weak or no H-bonding, unlike liquid water and most aqueous ionic salt solutions (Max *et al.*, 2007). According to Libowitzky (1999), O–H stretching frequencies in silicate minerals which are in excess of 3600 cm^{-1} correspond to O···O distances >~3.1–3.2 Å. In contrast to this estimated distance, the average O···O distance of liquid H_2O is ~2.8 Å, while the common perception of the H bond corresponds to O···O distances of <~3.1 Å (Khan, 2000). Lastly, the nearly constant intensity of the high-frequency band over broad ranges of water content indicates that the H_2O species responsible for this band is not sensitive to the actual expansion of the interlayer which does depend on water content (*cf.* Ferrage *et al.*, 2010). The origin of the sharp band from the water interface on the siloxane surface seems, therefore, the only valid mechanism, because its occurrence, position, and – on a qualitatively observable level – its intensity do not depend directly on the interlayer cation; neither does the band represent the bulk of the interlayer water.

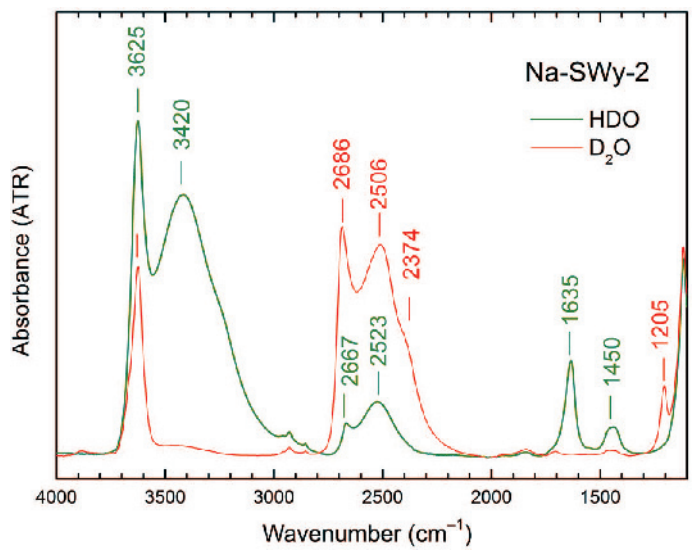


Figure 9. Comparison of the ATR-IR spectra of HDO- and D_2O-saturated Na-SWy-2 montmorillonite.

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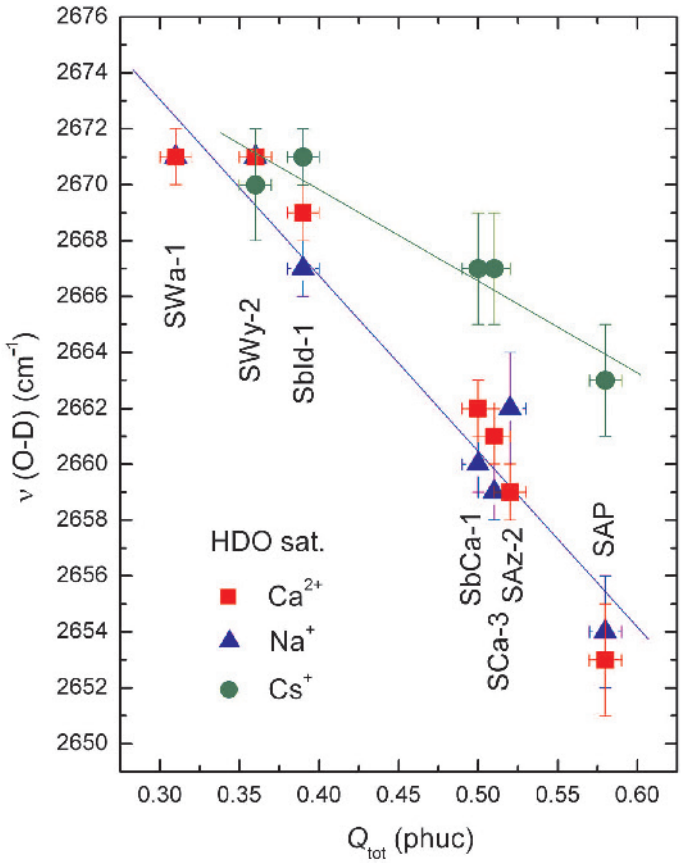


Figure 10. Same as Figure 8, based on HDO-saturated smectites.

O–H stretching bands at frequencies similar to or even greater than those reported here have been observed at the interface of H_2O with hydrophobic solids (*e.g.* silica, Jena and Hore, 2010) or liquids (*e.g.* CCl_4, Scatena *et al.*, 2001), or at the water–vapor interface (Sovago *et al.*, 2009; Tian and Shen, 2009) and are interpreted as modes of so-called 'dangling' OH (Shen and Ostroverkhov, 2006; Auer and Skinner, 2009; Sovago *et al.*, 2009; Tian and Shen, 2009; Zhang *et al.*, 2009; Chakraborty and Chandra, 2012; Davis *et al.*, 2012), *i.e.* vibration of OH groups that are involved in only very weak or non-existent interactions with other atoms. Notably, the siloxane surface of smectite is classified as mostly hydrophobic, based on aromatic-hydrocarbon adsorption experiments (Jaynes and Boyd, 1991).

In contrast, hydrophilic silica with surface SiOH and SiO^- groups exhibits no high-frequency component of the adsorbed water, as was shown using sum frequency vibrational spectroscopy (Shen and Ostroverkhov, 2006). After making the silica surface hydrophobic by coating it with organic molecules, the sharp, high-frequency band appeared (Shen and Ostroverkhov, 2006; Zhang *et al.*, 2009). Increasing the silica-surface hydrophobicity increased the intensity of the band and shifted the position of the band to higher frequencies (Zhang *et al.*, 2009).

The interpretation presented here is in accord with the conclusions of several early experimental studies on water–smectite interactions (*e.g.* Russell and Farmer, 1964; Farmer and Russell, 1971; Suquet *et al.*, 1977; Sposito and Prost, 1982; Sposito *et al.*, 1983) which identified the high-frequency OH_w band and linked it to H_2O molecules at the surface of the interlayer, pointing one of their O–H bonds towards the siloxane surface ('dangling') and the other towards the 'bulk' interlayer. Further support for this interpretation comes from theoretical studies of smectite hydration. Spatial arrangement of H_2O molecules with one or two OH directed toward the siloxane surface was proposed by the theoretical calculations of Prost and Chaussidon (1969) and the molecular dynamics simulations of Sposito *et al.* (1999), Suzuki and Kawamura (2004), Wang *et al.* (2005), and Marry *et al.* (2008).

Based on the considerations above, the high-frequency water OH(OD) stretching band is associated with water molecules at the interface with the siloxane sheet and with at least one OH(OD) group pointing toward the surface, *i.e.* in weak interaction with its siloxane O atoms and with negligible influence by interlayer

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cations. Indeed, within the resolution of the experiments performed, the only dependence of this band on the type of smectite was a small decrease in its frequency upon increasing layer charge. The observed shift of the band position was consistent with the development of some attractive interactions between the hydroxyl group of water and the increasingly charged 2:1 layer which would reduce the vibrational frequency of the dangling hydroxyl group. If confirmed on a large set of smectites, the high-frequency $OH(D)_w$ band may become a probe to measure the total layer charge of smectite.

CONCLUSIONS

The present study has provided new evidence in support of an old, sometimes forgotten idea about the structure of H_2O molecules in the interlayer space of smectite minerals. A population of H_2O located in the immediate vicinity of the siloxane surface and interacting very weakly with it has been identified by the ubiquitous presence of a high-frequency, sharp H_2O (D_2O) band at ~3630 cm^{-1} (2685 cm^{-1}). In dioctahedral aluminous smectites, this band nearly coincides with the stretching modes of the structural OH groups which may explain why it has not been identified in some studies as an H_2O vibration. The IR investigation of D_2O-saturated smectites, instead of the commonly studied H_2O analogs, re-emerges, therefore, as a valuable tool for the investigation of bands originating from both water molecules and structural OH groups, and free of the problematic overlap.

In agreement with early IR studies and recent studies of water at interfaces, the sharp, high-frequency H_2O (D_2O) band is assigned to O–H pointing away from the 'bulk' interlayer and toward the siloxane surface. The position of this band is nearly independent of the cation (Na^+, Ca^{2+}) and its intensity remained constant over broad hydration ranges, such as those achieved with 60–80% relative humidity at ambient temperature. A linear dependence of the sharp band position on the total layer charge of a smectite was found. Based on this dependence, it appears that the total layer charge, Q_{tot}, can be estimated from the position of the high-frequency O–D_w stretching band with an uncertainty of the order of ±0.03 e^-/half unit cell in Na- or Ca-smectites. This preliminary correlation is very promising and requires more data to confirm the trend. The relationship should be checked for the possible presence of systematics specific to octahedral structure (trioctahedral *vs*. dioctahedral, *cis*-vacant *vs*. *trans*-vacant) or charge location (octahedral *vs*. tetrahedral). A caveat that needs to be emphasized is that the exact position of the high-frequency OD_w depends on whether it is determined from maxima in absorbance spectra or minima in the 2nd derivative spectra. A 2nd derivative pre-processing of the spectra is recommended to improve the resolution of the sharp peak against the overlapping broad liquid-like band envelope. A calibration transfer may, therefore, be needed if the peak-picking algorithm is different from that employed in this work.

Finally, the identification of the OH_w contribution to the ~3620 cm^{-1} band of dioctahedral aluminous smectites is essential in assigning correctly the sharp ~5230 cm^{-1} near-IR feature (Cariati *et al.*, 1981, 1983) to a (ν+δ) stretching-bending combination of H_2O in smectites. The sharp band combination mode is particularly intense in the near-IR due to the effect of H-bonding on the anharmonicity of the O–H stretch (Sándorfy, 2006). This opens up the possibility of obtaining similar layer-charge diagnostics from the systematics of the (ν+δ) OH_w combination of H_2O in smectites using the near-IR, more conveniently and without the need for D_2O saturation of samples.

ACKNOWLEDGMENTS

The authors thank the editors and reviewers for valuable suggestions that helped to improve the manuscript. They are also grateful to Jarosław Kieć for technical assistance. This project was made possible with financial support from project REGPOT-2011-1 under the European Union 7th Framework Programme, No 285989 (ATLAB) and the IGS-PAS research grant for young scientists "Dehydration of smectites – a FTIR, TG and stable isotopes study". Partial support by project KRHPIS 447963 - Polynano (GSRT, TPCI-NHRF) is also acknowledged. This work was performed to partially fulfill the requirements of a PhD thesis by A. Kuligiewicz.

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(*Received 31 July 2014; revised 11 February 2015; Ms. 905; AE: A.G. Kalinichev*)

https://doi.org/10.1346/CCMN.2015.0630102 Published online by Cambridge University Press