A 40,000 yr record of clay mineralogy at Lake Towuti, Indonesia: Paleoclimate reconstruction from reflectance spectroscopy and perspectives on paleolakes on Mars

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ABSTRACT

Sediment deposited within lake basins can preserve detailed records of past environmental conditions on planetary surfaces, including both Earth and Mars. Establishing how to best characterize these paleoclimate records is thus critical for understanding the evolution of past planetary climates. Here, we present an ~40 k.y. lake sediment record from Lake Towuti, Indonesia, developed using visible to near-infrared (VNIR) reflectance spectroscopy. Source sediment from the main river input to Lake Towuti, the Mahalona River, is spectrally dominated by Mg-rich serpentine; however, we also identify a distinct Al-phyllosilicate component, which we interpret as kaolinite, that increases in relative proportion to serpentine with decreasing grain size. Sink sediment from two cores collected at the distal margins of the Mahalona River delta has similar spectral signatures to the input source sediment. The cores capture systematic variations in the proportion of Al-phyllosilicate to serpentine over time, which is also expressed in changes in bulk elemental chemistry of the sediment. We show that the abundance of serpentine relative to Al-phyllosilicate increases dramatically during the globally cooler, regionally drier climate of the Last Glacial Maximum. This change records the grain size–dependent mineralogy of deltaic sediment, which is ultimately driven by forced delta progradation and river incision during lake lowstands. Our analyses show that VNIR reflectance spectroscopy offers a rapid, nondestructive, and effective method for developing paleoenvironmental records from sedimentary phyllosilicate mineralogy. Exposed paleolake deposits on Mars should preserve similar paleoenvironmental information that can be accessed through detailed remote sensing observations of stratigraphy and VNIR reflectance spectroscopy in a source-to-sink framework.

INTRODUCTION

Lake basins on planetary surfaces are effective traps for sediment and can provide detailed records of the evolution of past environmental conditions throughout their lifetime of activity. Paleolimnological records are well known from Earth (e.g., Sly, 1978; Cohen, 2003), and paleolake basins have also been identified on Mars, where they provide some of the most convincing geologic evidence for ancient fluvial activity (e.g., Goldspiel and Squyres, 1991; Cabrol and Grin, 1999, 2001, 2010; Irwin et al., 2002, 2005; Malin and Edgett, 2003; Fassett and Head, 2005, 2008). While paleolake activity on Mars has been investigated with in situ rover analyses in a handful of locations (e.g., Christensen et al., 2004; Squyres et al., 2004a, 2004b; McGlynn et al., 2012; Grotzinger et al., 2014, 2015; McLennan et al., 2014; Mangold et al., 2016), the study of martian paleolake basins and associated sedimentary deposits is primarily restricted to the analysis of orbital remote sensing data (e.g., Goldspiel and Squyres, 1991; Cabrol and Grin, 1999, 2001, 2010; Irwin et al., 2002, 2005; Malin and Edgett, 2003; Fassett and Head, 2005, 2008; Ehlmann et al., 2008; Milliken and Bish, 2010; Ansan et al., 2011; Wray et al., 2011; Goudge et al., 2015).

A common remote sensing technique used to study the surface mineralogy of Mars is visible to near-infrared (VNIR) reflectance spectroscopy (e.g., Bibring et al., 2005, 2006; Mustard et al., 2005, 2008; Murchie et al., 2009; Ehlmann et al., 2011; Carter et al., 2013). VNIR reflectance spectroscopy studies how radiation in the VNIR portion of the electromagnetic spectrum interacts with a surface and is reflected back to a detector (i.e., a spectrometer). Minerals with infrared active components can have unique VNIR absorption features, and analysis of the precise position and shape of absorptions in an unknown measured spectrum can be used to confidently identify many of the minerals present (Farmer, 1974; Clark et al., 1990; Gaffey et al., 1993; Clark, 1999).

VNIR reflectance spectroscopy is particularly sensitive to vibrational absorptions caused by molecular components (e.g., H₂O, OH⁻, or CO₃²⁻) in the structure of minerals such as phyllosilicates (i.e., clay minerals) or carbonates. These molecular components have their fundamental vibrational absorptions in the mid-infrared (MIR) portion of the electromagnetic spectrum, which manifest as strong overtone and combination tone absorptions in the VNIR (Farmer, 1974; Clark et al., 1990; Gaffey et al., 1993). The sensitivity of infrared spectroscopy to H₂O and OH⁻ makes it an ideal tool for studying clay mineralogy. Previous workers have investigated the detailed structure of phyllosilicates using both MIR (e.g., Cuadros and Dudek, 2006) and VNIR (e.g., Petit et al., 1999) spectroscopy; however, VNIR reflectance spectroscopy has proved most useful for studying clay mineralogy on Mars (e.g., Bibring et al., 2005, 2006; Mustard et al., 2008; Murchie et al., 2009; Ehlmann et al., 2011; Carter et al., 2013).
VNIR reflectance spectroscopy has also been used to study the mineralogy and biogeochemical characteristics of lacustrine sediment from terrestrial lake basins, and has the potential for use in paleolimnologic studies (e.g., Bishop et al., 1996, 2003; Vogel et al., 2008; Rosén et al., 2010; Lynch et al., 2015; Weber et al., 2015). However, the sensitivity of VNIR reflectance spectroscopy to the presence of clay minerals in terrestrial lake sediment has yet to be widely exploited (e.g., Lynch et al., 2015; Weber et al., 2015).

Here, we use VNIR reflectance spectroscopy, complemented with more traditional laboratory analysis techniques, to study the mineralogy and chemistry of sediment from Lake Towuti, a large tectonic lake basin in Indonesia. We characterize the source-to-sink mineralogy of Lake Towuti and demonstrate the utility of VNIR reflectance spectroscopy for assessing paleoenvironmental signals preserved within lake sediment. We observe large changes in Lake Towuti sediment mineralogy and composition during the past ~40,000 yr that improve our understanding of lake sedimentation and regional climate variability for this basin. Our work also indicates that paleoenvironmental records may be developed through remote sensing analyses of paleolake deposits on Mars, which we suggest will be best achieved through careful analysis of both mineralogy and stratigraphy in the framework of a source-to-sink analysis (e.g., Milliken and Bish, 2010; Goudge et al., 2015).

METHODS

Lake Towuti, Indonesia—Geologic Context and Sampling

Lake Towuti (2.5°S, 121.5°E) is a hydrologically open lake located on the island of Sulawesi, Indonesia (Fig. 1). Lake Towuti has a surface...
area of ~560 km², a maximum depth of 203 m, and a catchment area of ~1500 km² (Russell et al., 2014). The catchment area primarily consists of laterites/Oxisols (Golightly and Arancibia, 1979; Soil Survey Staff, 1999) derived from, and overlain on, the East Sulawesi ophiolite, which is largely composed of harzburgite, dunite, and serpentinized lherzolite (Monnier et al., 1995; Kadarusman et al., 2004; Fig. 1B). Lake Towuti is fed by a number of river networks, although the primary input is the Mahalona River, which feeds the lake from the north (Fig. 1C) and supplies the majority of water and sediment flux to the basin (Costa et al., 2015).

For our source-to-sink analysis, we have focused on source sediment input to the lake from the Mahalona River, and sink sediment deposited at the distal margins of a delta deposit building out from the mouth of this river (Fig. 1C). We analyzed three sets of input sediment samples from the Mahalona River collected during the 2013 field season: (1) suspended load and (2) bed load sediment collected ~500 m upstream from the river mouth, and (3) river mouth sediment collected within the lake in water ~1 m deep. We also analyzed sink sediment from two cores ~10 m in length collected from both the eastern and southern distal margins of the Mahalona River delta (Fig. 1C). The two sediment cores, IDLE-TOW10-4B (herein referred to as TOW4) and IDLE-TOW10-5B (herein referred to as TOW5), were both collected from Lake Towuti during the 2010 field season using a modified Kullenberg piston corer.

Initial Sample Preparation

The Mahalona River sediment samples were freeze-dried, and bulk samples were sieved to grain sizes: >1 mm, 0.25–1 mm, 63–250 µm, 32–63 µm, and <32 µm. The bed load and river mouth samples were dry sieved, while the suspended load sample was wet sieved and subsequently freeze-dried. Bulk sample aliquots were also kept for analysis.

We extracted continuous 1–1.5-m-long subsamples (U-channels, ~2.5 x 2.5 cm in cross section) from the two sediment cores. The U-channels were frozen and freeze-dried using a custom-built polystyrene (PVC) chamber. Based on our analysis of the freeze-dried lake cores, we selected subsamples (11 from TOW4 and 10 from TOW5) from each of the two cores for further laboratory analysis. The subsamples were extracted from the original core sections and freeze-dried.

VNIR Spectroscopy

We measured the VNIR reflectance spectra of the input and core sediment using an Analytical Spectral Devices (ASD) FieldSpec 3 spectrometer, which covers the wavelength range 350–2500 nm at a spectral resolution of ~10 nm and a spectral sampling of 1 nm. VNIR spectra of the input sediment samples were measured with an external light source and the bare ASD fiber optic cable. Spectra of the two sediment cores were measured at 1 cm intervals along the entire core length using the ASD contact probe attached to the instrument stage of a Geotek™ multisensored core logger (MSCL). The scanned VNIR reflectance data for the two sediment cores were then converted from a data set relative to core depth (i.e., a spectrum each 1 cm along the entire length of core) to one relative to absolute age using linear interpolated age models (see the GSA Data Repository1 for additional details).

Major Element Chemistry

Major element chemistry (Al, Ca, Cr, Fe, K, Mg, Mn, Na, Ni, Si, and Ti) of the input sediment samples and lake core subsamples were measured using inductively coupled plasma-atomic emission spectrometry (ICP-AES). Prior to analysis by ICP-AES, aliquots of the samples were prepared via flux fusion using Li-metaborate flux following the methods of Murray et al. (2000). Aliquots of the bulk, >1 mm, 0.25–1 mm, and 63–250 µm input sediment grain-size separates were ground to <100 µm prior to flux fusion. All data are reported as wt% elemental oxide, with all Fe reported as FeO (see the GSA Data Repository for additional details on ICP-AES methods [see footnote 1]).

X-Ray Diffraction

Powder X-ray diffraction (XRD) data were collected for all of the grain-size separates of the input sediment samples. Prior to analysis, aliquots of the >1 mm, 0.25–1 mm, and 63–250 µm input sediment grain-size separates were ground to <45 µm. Randomly oriented samples were measured using a Bruker D2 PHASER instrument, and the data were analyzed using the Bruker DIFFRAC.EVA (v3.1) program, with the International Centre for Diffraction Data (ICDD) PDF-2 mineral database used for major mineral phase identifications. The Bruker D2 PHASER instrument uses a CuKα radiation source with a Ni filter that operates with 10 mA and 30 kV. Measurements were made with a 0.6 mm antiscatter shield, and a 2.5° Soller slit. Our samples were run over the 20 range 2°–70° with a step size of ~0.02°. We used a dwell time of 4 s per step for the >1 mm, 0.25–1 mm, and 63–250 µm input sediment grain-size separates, and 12 s per step for all other samples.

RESULTS

VNIR Spectroscopy

Input Sediment Samples

The VNIR reflectance spectra of the input sediment samples are characterized by a series of distinct vibrational absorptions related to the presence of phyllosilicate minerals (Fig. 2; Table 1). All of the grain-size separates are spectrally dominated by absorption features characteristic of Mg-rich serpentine, including narrow, vibrational absorptions centered at ~1390, 2150, and 2320 nm (Fig. 2). The absorption feature centered at ~1390 nm is caused by the first overtone of OH stretch, and the absorption feature centered at ~2320 nm is caused by a combination tone of Mg-OH bend and OH stretch (King and Clark, 1989; Clark et al., 1990). The broader absorption feature centered at ~2150 nm is characteristic of serpentine (King and Clark, 1989; Clark et al., 1990; Fig. 2D); however, the underlying structural cause of this absorption is not fully understood, although it is likely to be related to fundamental vibrational modes of Mg-OH (Clark et al., 1990).

Additionally, all of the input sediment spectra have a strong absorption centered near ~1900 nm (Fig. 2), which is caused by a combination tone of OH stretch and H-O-H bend from the H₂O (Gaffey et al., 1993; Clark et al., 1990). While the ideal formula of Mg-rich serpentine, Mg,Si₂O₅(OH)₄, contains no structural water, laboratory spectra of pure serpentine commonly show a broad ~1900 nm absorption due to either adsorbed water or small amounts of structural water (King and Clark, 1989; Clark et al., 1990; Fig. 2D).

The input sediment samples also exhibit several spectral differences associated with variations in grain size. The ~2150 nm absorption is greatly subdued with decreasing grain size (Fig. 2). Additionally, spectra of the finest grain-size separates (i.e., 32–63 µm and <32 µm) show a subtle absorption feature centered at ~2200 nm (Fig. 2), which is caused by a combination tone of Al-OH bend and OH stretch within the structure of an Al-bearing phyllosilicate, such as kaolinite or montmorillonite (Clark et al., 1990; Bishop et al., 2008). Finally, the shape...
of the ~1900 nm absorption feature exhibits changes associated with grain-size variations. The coarsest grain-size separates have a broad, “boxy” ~1900 nm absorption (Fig. 2), similar to that seen in laboratory serpentine (King and Clark, 1989; Clark et al., 1990; Fig. 2D). As grain size decreases, the width of the ~1900 nm absorption decreases, and it becomes more asymmetric (Fig. 2), similar to the ~1900 nm absorption feature seen for many other phyllosilicate minerals (Fig. 2D).

Differences in the spectra of the input sediment associated with variations in grain size may be due to either changes in the mineralogy of the samples or spectral effects associated with variations in grain size of a homogeneous material (e.g., Pieters, 1983; King and Clark, 1989; Mustard and Hays, 1997). The change in strength of the ~2150 nm absorption feature is likely to be due to the latter, as the same trend was observed by King and Clark (1989) in spectra of grain-size separates of pure serpentine. However, the cause(s) of the ~2200 nm absorption and the change in the shape of the ~1900 nm absorption is not as readily apparent.

To investigate this issue further, we took the coarsest grain-size separate (>1 mm) of the river mouth sediment and ground it to the same size fractions as the natural size separates. We then measured these powdered grain-size separates with the ASD FieldSpec and compared the spectra of the powdered and natural grain-size separates (Fig. DR1 [see footnote 1]). The change
### TABLE 1. MAJOR IDENTIFIED PHYLLOSILICATE ABSORPTION FEATURES

<table>
<thead>
<tr>
<th>Approximate absorption center (nm)</th>
<th>Structural cause</th>
<th>Reference(s)</th>
</tr>
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<tbody>
<tr>
<td>1390</td>
<td>First overtone of OH stretch (primarily serpentine in our samples).</td>
<td>King and Clark (1989), Clark et al. (1990)</td>
</tr>
<tr>
<td>1900</td>
<td>Combination tone of OH stretch and H-O-H bend in structural/adsorbed H₂O.</td>
<td>Clark et al. (1990), Gaffey et al. (1993)</td>
</tr>
<tr>
<td>2150</td>
<td>Characteristic of serpentine, but unassigned; likely related to vibrational modes of Mg-OH.</td>
<td>Clark et al. (1990)</td>
</tr>
<tr>
<td>2200</td>
<td>Combination tone of Al-OH bend and OH stretch in Al-phyllosilicate.</td>
<td>Clark et al. (1990), Bishop et al. (2008)</td>
</tr>
<tr>
<td>2320</td>
<td>Combination tone of Mg-OH bend and OH stretch in serpentine.</td>
<td>King and Clark (1989), Clark et al. (1990)</td>
</tr>
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</table>

in the strength of the ~2150 nm absorption occurs in both the natural and powdered grain-size separates; however, both the presence of an ~2200 nm absorption and the narrowing of the ~1900 nm absorption at finer grain sizes occur only in the natural grain-size separates (Fig. DR1 [see footnote 1]).

Therefore, we interpret these spectral changes to indicate mineralogic differences in the grain-size separates. The ~2200 nm absorption indicates a proportionally larger component of Al-rich phyllosilicate compared to Mg-rich serpentine in the finest grain-size separates. The narrowing of the ~1900 nm absorption indicates a change in the location of bound or adsorbed water. We interpret the cause of this change as a decrease in the relative amount of Mg-rich serpentine, which has a broad ~1900 nm absorption (King and Clark, 1989; Clark et al., 1990; Fig. 2D), in the finest grain-size separates.

The observed qualitative spectral changes (Fig. 2) can be readily quantified using spectral parameters, such as band depth (Clark and Roush, 1984; Clark, 1999; Pelkey et al., 2007). Absorption strength measured as a band depth (BD) is typically correlated with mineral abundance, and combinations of BD measurements provide discrimination among closely spaced absorption features (Clark and Roush, 1984; Clark, 1999; Pelkey et al., 2007). The primary parameter we make use of, BD1975:BD1915, quantifies the shape of the ~1900 nm absorption feature by comparing the relative absorption strength at 1975 and 1915 nm (Fig. 3; see the GSA Data Repository for additional details [see Footnote 1]).

![Figure 3. (A) Schematic explanation of the BD1975:BD1915 parameter, which quantifies the shape of the ~1900 nm absorption feature by comparing the relative absorption strength at 1975 and 1915 nm. Spectra with broader ~1900 nm absorptions will have larger BD1975:BD1915 values. (B) BD1975:BD1915 values vs. grain size for the input river mouth (diamonds), bed load (circles), and suspended load (squares) sediment from the Mahalona River. Right plot shows a histogram of BD1975:BD1915 values for cores TOW4 and TOW5. Note the similarity in absolute parameter values for the input and lake core sediment. (C–D) BD1975:BD1915 values vs. time for (C) core TOW4 and (D) core TOW5. Thin line indicates raw data, thick line is a 21 point moving average, and thickest line is a 101 point moving average. Triangles at bottom of both plots indicate locations of collected subsamples.](image-url)
footnote 1]). The BD1975:BD1915 parameter is also strongly negatively correlated to the band depth at 2200 nm (BD2200; Fig. DR2 [see footnote 1]), indicating this parameter accurately records the spectral differences we observe in association with variations in grain size.

Application of the BD1975:BD1915 parameter to the input sediment spectra shows, as expected, smaller BD1975:BD1915 values (i.e., narrower, more asymmetric ~1900 nm absorptions) for finer grain-size samples (Fig. 3B). An exception to this is the >1 mm grain-size separates, which have BD1975:BD1915 values that are lower than expected (Fig. 3B). We suggest that this is due to the very low albedo and low overall ~1900 nm band strength for these samples (Figs. 2A and 2B).

**Lake Cores**

VNIR reflectance spectra of the two sediment cores show the same primary vibrational absorption features as the input sediment, and both cores are spectrally dominated by serpentine along their entire length. However, qualitative analysis of the spectra from each of the cores reveals systematic changes in the down-core spectral signature. This is best observed in variations in BD1975:BD1915 values for each of the ~1000 spectra from the two cores, which show coherent variability (Figs. 3C and 3D). The absolute BD1975:BD1915 values of the sediment cores are also very similar to those of the input sediment (Fig. 3B), emphasizing the spectral similarity of the source and sink sediment.

The spectral parameter records from both cores show the same trends over the past ~20 k.y. (Figs. 3C and 3D), with a period of high BD1975:BD1915 values prior to ca. 17–15 ka, followed by a rapid transition to low

Figure 4. Variations in major element chemistry from inductively coupled plasma–atomic emission spectrometry (ICP-AES) data. (A) Al$_2$O$_3$ (wt%) vs. grain size and (B) MgO (wt%) vs. grain size for input river mouth (diamonds), bed load (circles), and suspended load (squares) sediment from the Mahalona River. (C, E) Al$_2$O$_3$ (wt%) vs. time and (D, F) MgO (wt%) vs. time for core TOW4 (C, D) and TOW5 (E, F) subsamples. The 21 point moving average of BD1975:BD1915 values versus time (Figs. 3C and 3D) is shown in the background for qualitative comparison. The y-axis scale for BD1975:BD1915 is inverted for the Al$_2$O$_3$ plot. Note that changes in major element chemistry track changes in spectral signature.
BD1975:BD1915 values in the Holocene, which persist from ca. 12 ka to the present. Core TOW4 ends at ca. 20 ka, during the phase of high BD1975:BD1915 values; core TOW5 shows low BD1975:BD1915 values (similar to Holocene levels) prior to ca. 35 ka that transition to the period of high values by ca. 27 ka (Fig. 3D).

Major Element Chemistry (ICP-AES)

Both the input sediment and lake core subsamples have distinct variations in their major element chemistry (Table DR1 [see footnote 1]). Al₂O₃, K₂O, NiO, Na₂O, and TiO₂ concentrations vary coherently and inversely to variations in MgO concentrations. CaO, Cr₂O₃, FeO, MnO, and SiO₂ concentrations show either very weak coherence with other major elements or no systematic variation.

Systematic trends in major element chemistry of both the input sediment samples and lake core subsamples are best observed through relative variations in Al₂O₃ and MgO concentration (Fig. 4). Input sediment samples have increasing Al₂O₃ concentration and decreasing MgO concentration with decreasing grain size (Figs. 4A and 4B). Thus, MgO concentration is positively correlated with BD1975:BD1915 values across varying sediment grain sizes, while the Al₂O₃ concentration trend is inverse to that of BD1975:BD1915 (Figs. 3B, 4A, and 4B). The lake core subsamples show a similar agreement with BD1975:BD1915 values, with Al₂O₃ concentration negatively correlated with BD1975:BD1915 and MgO concentration positively correlated with BD1975:BD1915 (Figs. 4C–4F).

Additionally, in both the input sediment samples and the lake core subsamples, the MgO concentration is generally higher than the Al₂O₃ concentration, by up to an order of magnitude in some cases (Fig. 4). This is consistent with our VNIR spectral interpretation that the samples are dominated by Mg-rich serpentine with a minor component of Al-rich phyllosilicate (Fig. 2).

X-Ray Diffraction

Results from XRD analysis of the input sediment samples indicate that the major mineral phase in all of these samples is serpentine (Fig. 5), consistent with our interpretation from VNIR reflectance spectroscopy (Fig. 2). Serpentine is identified from strong 001 and 002 reflection peaks, as well as a prominent 100 reflection. All of the samples also have a minor component of smectite, indicated by a weak 001 peak; however, the peak position and height do not vary significantly with grain size. Additionally, all but the >1 mm grain-size separates contain quartz, identified by 101 and 100 reflection peaks, which both increase in strength with decreasing grain size. The primary systematic variations in the XRD patterns of the input sediment grain-size separates are subtle changes to the 001 and 100 serpentine peaks (Fig. 5). As grain size decreases, the primary serpentine 001 peak develops a notable shoulder at slightly larger 20 values. Additionally, the position of the 100 serpentine peak near ~20° 20 shifts to slightly larger 20 values with decreasing grain size.

DISCUSSION

Overview of Lake Towuti Clay Mineralogy

VNIR spectra (Figs. 2 and 3) of river and lake sediment show that both the source sediment from the Mahalona River and the sink sediment from the Lake Towuti basin are dominated by Mg-rich serpentine. This conclusion is confirmed by XRD analyses of sample mineralogy (Fig. 5) and ICP-AES analyses of major element chemistry (Fig. 4; Table DR1 [see footnote 1]). This conclusion is also consistent with the catchment geology of the East Sulawesi ophiolite, which contains large regions of serpentinitized lherzolite (Kadarusman et al., 2004; Fig. 1B).

While serpentine is the dominant mineral phase in all of our samples, we also identify a distinct, systematically varying Al-rich phyllosilicate phase in both the input and lake sediment (Figs. 2–5). We interpret this Al-phyllosilicate to be kaolinite based on three primary observations from both our data and previous work on Lake Towuti sediment. First, Weber et al. (2015) identified kaolinite in sediment samples
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from Lake Towuti to the south of our study area based on VNIR spectra that show an ~2200 nm absorption with a distinct shoulder near ~2160 nm, which is diagnostic of kaolinite (Clark et al., 1990; Bishop et al., 2008). These sediments were finer grained and more Al-rich than our samples, which led to a more diagnostic ~2200 nm absorption.

The variations in the XRD patterns of our grain-size separates (Fig. 5) further suggest the presence of kaolinite. The position of the shoulder at larger 20 values on the serpentine 001 peak is consistent with the position of the kaolinite 001 peak. Additionally, the shift of the serpentine 100 peak near 20° 20 to larger 20 values with decreasing grain size is consistent with an increasing abundance of kaolinite, as the kaolinite 020 peak is at slightly larger 20 values than the serpentine 100 peak.

Finally, there are no systematic variations in the weak smectite 001 peak associated with changes in grain size (Fig. 5), which would be expected if the Al-phyllosilicate were an Al-rich smectite, such as montmorillonite. Therefore, we conclude that kaolinite is the most probable interpretation for the identified Al-phyllosilicate, and we refer to the identified Al-phyllosilicate as kaolinite in the rest of the discussion. However, we note that our interpretation of kaolinite is not a definitive identification and that our data are also potentially consistent with a different Al-rich phyllosilicate.

In both the input and lake sediment, we tracked the variation in kaolinite content relative to serpentine using our developed VNIR parameter BD1975:BD1915. While, strictly speaking, this parameter measures the shape of the ~1900 nm absorption due to structural/adsorbed water, it is a reliable proxy for the grain size–dependent mineralogy of our studied samples (Fig. 3). Calculated values of BD2200, which quantify the strength of the Al-OH absorption centered at ~2200 nm and more accurately capture the variation in kaolinite abundance, show the same trends as those observed in the BD1975:BD1915 parameter, and the two parameters are strongly negatively correlated (Fig. DR2 [see footnote 1]). However, many of our measured samples have no clear absorption at ~2200 nm (Fig. 2), which results in a BD2200 value of 0 (Fig. DR2 [see footnote 1]). In contrast, measured BD1975:BD1915 values vary continuously from ~0.5 to 0.9 (Fig. 2), making for easier data analysis and interpretation. Furthermore, the general sublety of the ~2200 nm absorption (Fig. 2) leads to increased scatter in the trends for BD2200 as compared to BD1975:BD1915, which again hinders data interpretation.

In the input sediment, the proportion of kaolinite increases relative to serpentine with decreasing grain size (Figs. 2–5). In the lake sediment, the proportion of kaolinite relative to serpentine is high prior to ca. 35 ka, during marine isotope stage 3 (MIS 3), lowest from ca. 27–17 ka, during the Last Glacial Maximum (LGM), and again high from ca. 12 ka to the present, during the Holocene. There are also higher-frequency fluctuations in the proportion of kaolinite to serpentine superimposed on these orbital-scale trends (Figs. 3C and 3D).

Based on the similarity of both the spectral signature (Fig. 3) and elemental chemistry (Fig. 4; Table DR1 [see footnote 1]) of the input source compared to the lake sink sediment, we conclude that the core sediment is primarily detrital in origin and that there is no evidence for major in situ alteration or authigenesis of phyllosilicate minerals. This conclusion is consistent with the relatively low salinity of Lake Towuti (Costa et al., 2015), as in situ alteration and authigenesis of phyllosilicate minerals is most common in highly alkaline and saline lakes (e.g., Jones and Weir, 1983; Deocampo et al., 2009). The provenance of this detrital sediment represents a mix of materials from Lake Towuti’s catchment, including primary phases from the serpentinized East Sulawesi ophiolite (Kadarusman et al., 2004) and pedogenic alteration phases from laterites/Oxisols (Golightly and Arancibia, 1979; Golightly, 1981; Soil Survey Staff, 1999).

Variation in Input Sediment Mineralogy

The systematic variation in the proportion of kaolinite to serpentine with changes in grain size of the input sediment (Figs. 2–5) indicates that there is mineralogic sorting operating in the catchment of the Mahalona River, or perhaps within the river itself, whereby kaolinite is preferentially accumulated in finer grain sizes compared to serpentine. Al-rich alteration phases, such as kaolinite, are expected only with progressive alteration of crustal materials due to the relative stability of Al to leaching (e.g., Nesbitt and Young, 1982, 1989; Nesbitt and Wilson, 1992). Lake Towuti’s catchment is characterized by highly weathered laterites/Oxisols that are enriched in Al, Fe, Cr, and other recalcitrant elements relative to the underlying parent bedrock, which is enriched in Mg, among other leachable elements (Golightly and Arancibia, 1979; Golightly, 1981; Soil Survey Staff, 1999).

The relationship between grain size and alteration can be tested using the chemical index of alteration (CIA), which is a measure of the overall degree of chemical weathering of a sample (Nesbitt and Young, 1982). The original formulation of the CIA was developed for upper-crustal materials such as granite or basalt (Nesbitt and Young, 1982, 1989; Nesbitt and Wilson, 1992); however, our sediment samples—derived from the partially serpentinized East Sulawesi ophiolite (Kadarusman et al., 2004)—have very low concentrations of CaO, Na2 O, and K2 O (<2 wt%; Table DR1 [see footnote 1]). The labile oxides traditionally used to calculate CIA. This makes calculation of CIA values less robust and more prone to influence from sample variability and systematic propagation of measurement error. Therefore, we used a modified CIA value to incorporate MgO as a labile oxide, since MgO is expected to leach out of basaltic and mafic materials before Al2 O3 (Nesbitt and Wilson, 1992). The modified CIA is calculated as:

$\text{modified CIA} = \frac{\text{Al}_2 \text{O}_3 / (\text{Al}_2 \text{O}_3 + \text{CaO} + \text{Na}_2 \text{O} + \text{K}_2 \text{O} + \text{MgO}) \times 100}{1}$

where all the oxide values are in molecular proportions, and higher values indicate increased degrees of chemical weathering (Nesbitt and Young, 1982).

The river input sediment samples show a clear trend of increasing modified CIA values with decreasing grain size (Fig. 6A). The same general trend is observed with traditional CIA values, although there is increased scatter due to the low overall concentrations of CaO, Na2 O, and K2 O (Table DR1 [see footnote 1]). The river input sediment samples also show a distinct trend of increasing TiO2/Al2 O3 ratios with decreasing grain size (Fig. 6B). Ti-rich phases are typically more resistant to chemical weathering than Al-rich phases, and in heavily leached soils, TiO2/Al2 O3 ratios are expected to increase in the most weathered portions of the soil profile (e.g., Young and Nesbitt, 1998).

Therefore, these data indicate that the finest grain-size input sediment has experienced the highest degree of chemical alteration and leaching, including loss of MgO. In light of the chemical gradients that exist in regional soil profiles (Golightly and Arancibia, 1979; Golightly, 1981), we conclude that the increase in the proportion of kaolinite to serpentine in the finest grain-size separates of the Mahalona River input sediment is primarily controlled by varying sources of the detrital sediment from the Lake Towuti catchment. The fine, more chemically weathered, kaolinite-enriched sediment is derived from fluvial erosion and transport of the heavily leached soil (Golightly and Arancibia, 1979; Golightly, 1981). In contrast, the coarse, less chemically weathered, serpentine-rich sediment is derived from fluvial erosion and transport of bedrock, i.e., the
serpentinized East Sulawesi ophiolite (Kadrusman et al., 2004).

**Variation in Lake Core Mineralogy**

Our ~40 k.y. VNIR spectroscopy record of clay mineralogy from the Mahalona River delta sediment shows coherent changes in the relative abundances of kaolinite and serpentine through time (Figs. 3C and 3D). We hypothesize that this variation in mineralogy is controlled by systematic changes over time in: (1) the chemical weathering intensity on the landscape and/or (2) the relative proportion of fine versus coarse sediment accumulated at the core sites.

Changes in the chemical weathering intensity on the landscape would change the proportion of kaolinite produced from chemical weathering of the partially serpentinized East Sulawesi ophiolite. In theory, decreased chemical weathering intensity would lead to a decreased proportion of kaolinite in the weathered soil (Goldightly and Arancibia, 1979; Nesbitt and Young, 1982, 1989; Nesbitt and Wilson, 1992). Assuming no change in physical transport processes, this should result in a decrease in the amount of kaolinite input to the basin relative to serpentine.

Changes in the dominant grain size accumulated at the core sites should also result in a change in mineralogy given the strong grain size dependence we observe in input sediment composition (Figs. 2–5). Decreased input (e.g., by changes in the grain-size distribution of input sediment) or accumulation (e.g., by changes in hydrodynamic sorting processes during transport and deposition) of fine-grained sediment at the distal margins of the Mahalona River delta would result in a decrease in the proportion of kaolinite compared to serpentine in the cores.

To test between these two hypotheses, we examined lacustrine grain-size separates of three sediment core subsamples collected from pelagic clay beds spanning a wide range of ages (ca. 11.6 ka to ca. 32.0 ka). While the fine-grained nature of the samples precludes analyses of coarse sediment fractions, VNIR reflectance data from these subsamples show that the finest grain-size separates (<32 µm) have a stronger ~2200 nm absorption and a weaker ~2320 nm absorption than the coarser, 32–63 µm fraction (Fig. 7). This observation is consistent with an increasing component of kaolinite relative to serpentine in the finest grain-size separates, as is also seen for modern input sediment (Figs. 2 and 3). Similarly, ICP-AES analyses show that the lake core subsamples have an MgO/Al2O3 ratio that is very similar to values for the same grain sizes of modern input sediment (Fig. 8).

Taken together, these data suggest that there are similar proportions of kaolinite to serpentine in the silt and clay grain-size fractions of both the modern input sediment and the lake core sediment. Furthermore, the lake core subsample grain-size separates have similar modified CIA values (Fig. 6A) and TiO2/Al2O3 ratios (Fig. 6B) as modern input sediment, indicating similar degrees of chemical weathering for the same grain-size fractions through time. These data argue against dramatic changes in chemical weathering intensity at this site over the past ~40 k.y.

While this result may seem surprising in light of paleoclimate records that document a drier climate from ca. 33 to 16 ka in this region during the LGM (e.g., Russell et al., 2014), we suggest that the Lake Towuti basin remained warm and moist enough to maintain strong chemical weathering throughout this time period. Therefore, we conclude that the observed changes in the mineralogy and spectral signature of the sediment cores (Figs. 3C and 3D) are primarily indicative of grain size–controlled variations in the relative proportion of (fine) kaolinite compared to (coarse) serpentine accumulated at the core sites over the past ~40 k.y. This conclusion is also consistent with the sedimentologic analysis of Vogel et al. (2015).

**VNIR Spectroscopy as a Paleoenvironmental Record**

Modern Holocene sediment in both cores is composed of fine-grained material that is enriched in kaolinite (Figs. 3C and 3D). During MIS 3, prior to ca. 35 ka, sediment deposition at the TOW5 site was similar to Holocene conditions, with deposition of fine-grained, kaolinite-enriched sediment. This was followed by a gradual transition to an interval composed of serpentinite-rich, coarse-grained sediment, from ca. 27 to 17 ka, i.e., during the LGM. We have no record of MIS 3 in core TOW4, but both cores record a relatively abrupt ~3–5 k.y. transition during the last glacial termination to the regime of kaolinite-enriched, fine-grained sediment deposition occurring from ca. 12 ka to the present.

What was the cause for the period of deposition of serpentinite-rich, coarse-grained sediment during the LGM? One potential explanation is an increase in the discharge of the Mahalona River, which might be expected to lead to increased fluvial transport of coarse sediment. However, increased surface runoff should also deliver more fine-grained, kaolinite-enriched sediment to the basin, which may lead to a nonlinear net change in the proportion of transported serpentinite to kaolinite with increasing discharge. Furthermore, recent work on geochemical and sedimentological proxy records from Lake Towuti has shown that during the last glacial period, from ca. 33 to 16 ka, this part of Indonesia experienced relatively drier conditions compared with the Holocene and MIS 3 (Russell et al., 2014; Costa et al., 2015; Tamuntuan et al., 2015; Vogel et al., 2015).

Increased hydrodynamic sorting processes, namely, winnowing of fine-grained sediment from strong bottom currents, could also lead to a decrease in the amount of kaolinite accumulated at the core sites during the LGM. Changes in hydrodynamic sorting processes within the basin would be expected in association with major changes in lake level and circulation, and indeed previous workers have shown that water levels in Lake Towuti dropped during the drier LGM interval (Russell et al., 2014; Costa et al., 2015; Tamuntuan et al., 2015; Vogel et al., 2015).

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**Figure 6.** (A) Modified chemical index of alteration (CIA) values and (B) TiO2/Al2O3 ratios vs. grain size for the input river mouth (diamonds), bed load (circles), and suspended load (squares) sediment from the Mahalona River, as well as the grain-size separates of lake core subsamples C4-7, C5-5, and C5-8 (triangles). Symbol for the lake core subsamples is the mean value, and error bars denote the range of values. TiO2/Al2O3 ratios were calculated in molar proportions.
However, Vogel et al. (2015) demonstrated that water level changes in the Lake Towuti basin during the LGM were on the order of tens of meters, which would be insufficient to drive significant changes in lake circulation and hydrodynamic sorting processes affecting the distal portions of the Mahalona River delta.

Instead, we interpret the increase in coarse-grained, serpentine-rich sediment in the two cores during the LGM as a signal of multiple sedimentologic processes internal to the Lake Towuti basin driven by the Mahalona River and delta responding to the external forcing of a drier climate. Lower water levels in Lake Towuti, such as those experienced during the LGM (Russell et al., 2014; Costa et al., 2015; Tamuntuan et al., 2015; Vogel et al., 2015), should cause progradation of the Mahalona River delta, exposure of coarse-grained topset sediment, and increased river incision due to the fall in local base level. Delta progradation would cause increased coarse sediment deposition further into the basin, including at the core sites, which would have been enhanced by the readily available coarse-grained topset sediment exposed from lowered lake levels. As suggested by sedimentologic analyses (Vogel et al., 2015), additional coarse sediment was delivered to the core sites through discrete slumping and turbidity current events along the delta front. The drop in local base level from lower Lake Towuti water levels would also have driven increased bedrock incision by the Mahalona River. The resultant increase in fluvially transported coarse-grained, bedrock-derived sediment relative to fine-grained, soil-derived sediment would cause an increase in the amount of serpentine delivered.

Figure 7. Visible to near-infrared (VNIR) reflectance spectra of the grain-size separates of lake core subsamples (A) C4-7, (B) C5-5, and (C) C5-8. Top plots show full VNIR reflectance spectra. Dashed lines are located at ~1400, 1900, 2100, 2200, and 2320 nm. Bottom plots show continuum-removed reflectance in the ~2200–2400 nm region, showing a stronger ~2200 nm absorption and a weaker ~2320 nm absorption for the <32 μm grain-size fraction. Dashed lines are located at ~2205 and 2325 nm. Continuum-removed reflectance was calculated by dividing the original spectrum by a continuum spectrum calculated using a convex hull method.

Figure 8. MgO/Al₂O₃ (in molar proportions) vs. grain size for the input river mouth (diamonds), bed load (circles), and suspended load (squares) sediment from the Mahalona River, as well as the grain-size separates of lake core subsamples C4-7, C5-5, and C5-8 (triangles). Symbol for the lake core subsamples is the mean value, and error bars denote the range of values (range for <32 μm samples is smaller than the symbol).
to the basin relative to kaolinite. All of these processes would result in increased deposition of coarse-grained, serpentinite-rich sediment relative to fine-grained, kaolinite-enriched sediment at the distal deltaic core sites during the drier LGM climate, a signal that is accurately captured by our VNIR spectroscopy record (Figs. 3C and 3D).

A comparison of our VNIR spectroscopy record to previous paleoclimate reconstructions from Lake Towuti (Russell et al., 2014) shows highly consistent trends (Fig. 9); however, there are notable systematic differences between our VNIR spectroscopy record and the record presented by Russell et al. (2014). In particular, our VNIR spectroscopy record captures a cyclic variation in the Mahalona River delta mineralogy with a period of ~11 k.y. superimposed upon the MIS 3/2/1 trends (Fig. 9).

Interestingly, this periodicity is suggestive of a half-precession rainfall cycle. At the equatorial latitude of Lake Towuti, insolation is strongest during both the spring and fall equinoxes (Berger, 1978; Fig. 9), which coincide with the twice-annual passage of the tropical rain belt over the equator. Equatorial rainfall might therefore exhibit a half-precession cycle if the intensity of rainfall within the tropical rain belt responds to the strength of local insolation during the spring and fall equinoxes, which each oscillate on a 21,000 yr cycle due to Earth’s precession (Short et al., 1991; Fig. 9).

In the present day, seasonal precipitation at Lake Towuti does peak during March and April as the tropical rain belt migrates over the equator (Russell et al., 2014). Speleothem-based rainfall reconstructions from nearby Borneo also suggest that changes in rainfall and convection corresponded to variations in boreal fall (September to November) insolation intensity during the last glacial cycle (Carolin et al., 2013). However, Lake Towuti experiences a dry season during boreal fall due to local air-sea interactions (Hendon, 2003). More importantly, during the past 40,000 yr, boreal spring and fall insolation at the equator peaked at ~6, 17, 28, and 39 k.y. B.P., which correspond to drier intervals in our record (Fig. 9).

Instead, wetter time periods in our data align most closely with insolation maxima during austral and boreal summer (December and June, respectively; Fig. 9). Thus, our data may indicate that the half-precession cycle observed at Lake Towuti reflects the intensification of the austral and boreal summer Asian monsoons. Similar dynamics have been observed in a record from equatorial East Africa (Verschuren et al., 2009); however, a longer paleoclimate record from Lake Towuti is needed to robustly document the relationship between insolation and rainfall through the Pleistocene.

Regardless, the general coherence between our VNIR spectroscopy record and a more traditional geochemical proxy record (Russell et al., 2014; Fig. 9) clearly indicates that our record accurately captures the major paleoclimatic forcings affecting this basin over the past ~40 k.y. Our approach of core scanning VNIR reflectance spectroscopy provides an effective method for rapidly and nondestructively characterizing the phyllosilicate mineralogy of terrestrial lake sediment. Our results show that this technique can be used to develop high-resolution records of paleoenvironmental change, similar to records from more traditionally used geochemical proxies (e.g., Hughen et al., 2004; Castaneda et al., 2009; Russell et al., 2014).

Implications for Paleolakes on Mars

The ultramafic nature of the East Sulawesi ophiolite (Monnier et al., 1995; Kadarusman et al., 2009) makes the Lake Towuti catchment area compositionally comparable to the mafic, basaltic martian crust (e.g., Mustard et al., 2005; McSween et al., 2009); however, the specific alteration mineral phases that dominate the input and lake sediment in the Lake Towuti system (serpentine and kaolinite) are not as commonly identified on the martian surface as other

Figure 9. (A) Previously published paleoclimate reconstruction from Lake Towuti sediment, 813C wax (Russell et al., 2014), compared to (B–C) BD1975:BD1915 values vs. time for core TOW4 (B) and core TOW5 (C) and (D–G) equatorial insolation curves. Note the coherence of the overall structure for the top three records (A–C). Interpretations for driving mechanisms of variation in both 813C wax and BD1975:BD1915 values are shown on right. Vertical gray bars highlight periods with insolation maxima at the winter and summer solstices, which correspond to wetter time intervals in our visible to near-infrared (VNIR) spectroscopy record. The Russell et al. (2014) paleoclimate reconstruction was developed using 813C wax, a proxy for regional precipitation based on carbon isotopic values of terrestrial leaf waxes buried in lacustrine sediment. Insolation curves were calculated for the fall (D) and spring (E) equinoxes and the winter (F) and summer (G) solstices at 0° latitude using the Analysers software package (Paillard et al., 1996).
basaltic weathering products, primarily Fe- and Mg-rich smectites (e.g., Poulet et al., 2005; Bibring et al., 2006; Mustard et al., 2008; Ehlmann et al., 2011; Carter et al., 2013, 2015). Although this is the case, our spectral record of Lake Towuti sediment demonstrates that VNIR reflectance spectroscopy can provide a detailed record of paleoenvironmental changes over a period of tens of thousands of years (Fig. 9). The sedimentary rock record on Mars should also preserve distinct paleoenvironmental signals that can be studied in a similar fashion with combined analyses of high-resolution, remote sensing observations of stratigraphy and VNIR spectroscopy (e.g., Wray et al., 2008, 2011; Loizeau et al., 2010; Milliken and Bish, 2010; Milliken et al., 2010; Ansan et al., 2011).

Major variations in the orbital spectral signature of exposed stratigraphic sections on Mars have previously been interpreted to indicate changes in environmental weathering conditions (e.g., Wray et al., 2008; Loizeau et al., 2010; Milliken et al., 2010) or protolith material (e.g., Loizeau et al., 2010). However, our results from Lake Towuti demonstrate that major changes in sedimentary spectral signatures can also be driven by grain size-controlled mineralogy and the internal response of sedimentary systems to external environmental forcing factors, and these factors should also play a role in controlling mineralogic variations in sedimentary environments on Mars.

Indeed, in situ analyses from the Mars Exploration Rovers and Mars Science Laboratory have revealed the potential effects of hydrodynamic sorting and grain size–dependent mineralogy on the composition of both modern surface soils (e.g., McGlynn et al., 2012; Meslin et al., 2013) and exposed sedimentary rocks (e.g., Christensen et al., 2004; Grotzinger et al., 2014; McLennan et al., 2014; Mangold et al., 2016). Building upon these results, Fedo et al. (2015) used laboratory studies to show that hydrodynamic sorting in an eolian environment has a significant effect on the composition and mineralogy of sediment derived from an unaltered basaltic protolith. Therefore, it is entirely possible that stratigraphic variations in VNIR spectral signatures of exposed martian sedimentary deposits are due to grain size–controlled mineralogy, as opposed to weathering or protolith changes (e.g., Wray et al., 2008; Loizeau et al., 2010; Milliken et al., 2010).

Although mineralogic variations of martian sedimentary deposits due to weathering or protolith changes are enticing for inferring paleoenvironmental changes on Mars (e.g., Wray et al., 2008; Loizeau et al., 2010; Milliken et al., 2010), our results from Lake Towuti demonstrate that records of grain size–dependent mineralogy can also offer detailed paleoenvironmental information (Fig. 9). We thus emphasize both the importance and utility of considering hydrodynamic sorting as a mechanism for driving mineralogic variation within sedimentary deposits on Mars. Furthermore, our results show that processes of hydrodynamic sorting and the resultant effects on sedimentary mineralogy can be accurately characterized using VNIR spectroscopy in a source-to-sink framework, an approach that can be readily applied to orbital remote sensing studies of the sedimentary rock record of Mars (e.g., Milliken and Bish, 2010; Goudge et al., 2015).

Martian paleolake deposits, in particular, are highly suitable for analysis of mineralogy using a source-to-sink approach, because they often have a clear regional geologic context; however, there have been relatively few source-to-sink mineralogy studies of paleolake systems on Mars (e.g., Milliken and Bish, 2010; Goudge et al., 2015). Our results from Lake Towuti suggest that future studies of paleolake deposits on Mars using VNIR reflectance spectroscopy may be able to extract unique information on fluvial hydrodynamic sorting processes, in addition to records of paleoenvironmental change. Such information will be crucial for testing competing hypotheses of the evolution of ancient aqueous surface environments on Mars and, in particular, two of the end-member hypotheses that invoke significantly different climatic and geochemical conditions: a warm and wet early Mars with widespread surface weathering (e.g., Craddock and Howard, 2002; Carter et al., 2013, 2015) or a cold and icy early Mars with limited surface weathering and more widespread subsurface alteration (e.g., Ehlmann et al., 2011; Wordsworth et al., 2013; Head and Marchant, 2014).

CONCLUSIONS

We used VNIR reflectance spectroscopy to assess the source-to-sink mineralogy of Lake Towuti, a hydrologically open lake in Indonesia. Our results show that the input sediment from the Mahalona River is spectrally dominated by Mg-rich serpentine, with an increasing component of Al-phyllosilicate, which we interpret as kaolinite, with decreasing grain size (Figs. 2 and 3B). Two sediment cores collected from the distal margins of the Mahalona River delta show similar overall spectral signatures to the input sediment (Fig. 3), suggesting a limited impact of clay authigenesis on the phyllosilicate mineralogy in the lake.

The VNIR spectral records from both cores show coherent, systematic trends over the past ~40 k.y. (Figs. 3C and 3D), which we conclude were controlled by changes in mineralogic related to variations in the dominant grain size deposited at the core sites over time. Fine-grained, Al-phyllosilicate–enriched sediment was deposited at the core locations during the Holocene (ca. 12–0 ka) and MIS 3 (prior to ca. 35 ka). During the LGM, from ca. 27 to 17 ka, the core sites received coarse-grained, serpentine-rich sediment. We conclude that this change in grain size and associated mineralogy was driven by a drier regional climate and a drop in the Lake Towuti water level (Russell et al., 2014; Costa et al., 2015; Tamontuan et al., 2015; Vogel et al., 2015), which forced delta progradation, exposure and offshore transport of coarse-grained topset sediment, and increased river incision into serpentine-rich bedrock.

Our VNIR spectroscopy record is highly consistent with geochemical proxy records for the Lake Towuti basin over the past ~40 k.y. (Russell et al., 2014; Fig. 9), and it captures changes in delta dynamics, lake level, and regional precipitation over this time period. VNIR reflectance spectroscopy offers a relatively rapid, nondestructive method for assessing the phyllosilicate mineralogy of modern lake sediments (e.g., Bishop et al., 1996, 2003; Vogel et al., 2008; Rosén et al., 2010; Lynch et al., 2015; Weber et al., 2015). Our results demonstrate the utility of VNIR reflectance spectroscopy, in combination with a core scanning approach, for providing detailed, high-resolution records of past environmental change preserved in sediments from terrestrial lake basins.

Paleolake deposits on Mars are also likely to contain similar paleoenvironmental information that can be accessed with remote VNIR reflectance spectroscopy. Interpretation of VNIR reflectance spectroscopy data requires careful analysis, and we emphasize the importance of mineralogic grain-size sorting (e.g., Christensen et al., 2004; McGlynn et al., 2012; Meslin et al., 2013; Grotzinger et al., 2014; McLennan et al., 2014; Mangold et al., 2016) as a potential control on observed spectral signatures. Future studies of martian paleolake deposits aimed at paleoenvironmental reconstructions will greatly benefit from combined stratigraphic and spectral analyses, as well as mineralogic analysis in the framework of a source-to-sink approach, which has been applied to only a select few martian paleolake systems to date (e.g., Milliken and Bish, 2010; Goudge et al., 2015).

ACKNOWLEDGMENTS

We express our gratitude to Associate Editor Andrew Cohen and two anonymous reviewers for their insightful and constructive comments, and to David Schofield for editorial handling. We thank Rebecca Greenberger, Io Wicaksono, Danielle Carens, Dave Murray, Joe Orchard, Tom Kiefer, Taki Hiroi, and especially Kevin Robertson for their help with various
components of sample preparation, laboratory tech-
niques, and data analysis. We also thank Ralph Mil-
lik for use of his X-ray diffraction instrument and help-
ful discussions, and Hendrik Vogel for sharing a
preprint of his work and helpful discussions. Goudge
gratefully acknowledges support for this work from
the Natural Sciences and Engineering Research Coun-
cil of Canada (NSERC) Postgraduate Scholarships
Program (PGS3-421594-2012). Head acknowledges
support from National Aeronautics and Space Ad-
ministration (NASA) Mars Data Analysis Program
grant NNX11A18G. Russell acknowledges support
from National Science Foundation grant EAR-1401448.

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