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Spectral properties of foliose and crustose lichens based on laboratory experiments

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Abstract

Reflectance spectra of rock encrusting lichens were acquired to determine the influence that this vegetation type may have on the reflectance properties of rock exposures located in high latitude and subarctic environments. The samples investigated consist of crustose and foliose lichen species collected from exposures of the Gog quartzite formation in Alberta, Canada. Lichen transmittance was estimated to be <3% throughout the 350–2500-nm spectral region, using spectra measured from the foliose lichen, *Umbilicaria torrefacta*, as a representative sample of a broader class of lichens. These findings suggest that lichen prevents the transmission of light to the underlying rock substrate. Therefore, the subpixel influence of lichen and rock within a scene can be considered linearly weighted. Discrimination of lichen species is made possible using ratios of reflectance at 400/685 and 773/685 nm. An index using the band ratios 2132/2198 and 2232/2198 nm shows the similarity of lichen spectra in the infrared and a distinguishing feature between rocks with OH bearing minerals and lichen. Thus, spectral unmixing of rock and crustose/foliose lichens may be successfully accomplished using a single lichen end-member for this spectral range.

1. Introduction

Hyperspectral remote sensing systems are becoming increasingly available for regional geological mapping and mineral exploration where cost saving measures are key to commercial competitiveness (Kruse, 1999; Staenz, Szeredi, & Schwarz, 1998). The mixture of several materials within individual pixels can complicate the analysis of multi and hyperspectral information, often masking the diagnostic spectral features of materials of interest and hampering their classification. A widespread example of this problem in high latitude, subarctic regions is the ubiquitous presence of lichens covering exposed rocks that may compromise the ability to map the reflectance signatures of minerals from imaging spectrometer data (Rivard & Arvidson, 1992). In tundra and open woodland habitats, lichens and mosses can cover an area by as much as 70% (Solheim, Engelsen, Hosgood, & Adreoli, 2000), making it difficult to develop comprehensive mapping exercises aimed at resource extraction. Fortunately, the use of spectral mixture analysis (SMA) as described by (Mustard & Sunshine, 1999; Smith, Ustin, Adams, & Gillespie, 1990) addresses the complexity of target identification within mixed pixels and can allow detection of substances exposed at subpixel resolution. Typically this approach assumes that mixed spectra result from the linear combination of spectral end-members (Singer & McCord, 1979). The spectra of end-members are either extracted from the imagery or measured in the laboratory or in the field.

Rock coatings (nonbiogenic and biogenic) are scattering/transmitting layers with optical thickness that can vary with material properties and wavelength. Lichens and desert varnish are examples of biogenic and nonbiogenic rock coatings. Desert varnish is a nonbiogenic patina of mixed-layer illite clays and nanocrystalline iron and manganese oxides partially covering rock surfaces in Earth's deserts (Potter & Rossman, 1977; Rivard & Arvidson, 1992; Sultan, Arvidoson, Sturchio, & Guiness, 1987). We know that varnish can, in instances, completely mask the spectral signature of underlying rock material, but in general, it is optically thin (between 400–2500 nm) to the underlying bedrock (Rivard & Arvidson, 1992). The use of a representative spectral end-member for varnish in SMA and the simplifying assumption of linear mixing

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typically used for this analysis can therefore be complicated in instances where varnish is partially translucent to the rock substrate.

Lichens, mosses and cyanobacteria are specific examples of biological coatings known as lithobionts. The spectral properties of lithobionts have been the focus of a number of studies (Karnieli & Tsoar, 1995; Karnieli et al., 1996; Tommervik, Johansen, & Lauknes, 1997) that report similarities with higher plants as well as key spectral distinctions. Examples of similarities and distinctions are discussed below in Section 3.1. However, to date there is minimal literature that thoroughly describes the spectral characteristics of rock encrusting lichens (Solheim et al., 2000). A study of spectral characteristics specific to lichen on granitic rock surfaces was performed by Satterwhite, Henley, & Carney (1985), but the data were limited to the 400–1100-nm range, which excludes the short wave infrared region exploited by many hyperspectral instruments relevant to the analysis of geological targets. Petzold and Goward (1988) focused on *Cladina* (a dominant boreal forest and low arctic tundra lichen) and also reported results limited to the 380–1100-nm region. Ager and Milton (1987) reported spectra covering the region from 400 to 2500 nm and attributed the variation of spectral characteristics of lichen solely to colour. While colour is a key spectral attribute of lichens, this study reports spectral distinctions in different species of lichens of the same colour. Rivard and Arvidson (1992) examined spectral features distinct to rock encrusting lichens based on a small number of measurements, but failed to identify the species of lichens used in their analysis, therefore, limiting the use of their results.

An important issue in the study of the spectral reflectance of lithobionts is the lack of information on their ability to transmit light photons. The suggestion that lichens do not transmit light was made early on by Gates (1980) who reported that lichens have low transmittance, though no measurements were presented to support this statement. Ager and Milton (1987) reported unpublished transmittance results of green and brown foliose lichens acquired by J. Salisbury at John Hopkins University. The reported transmittance values did not exceed 0.15% between 2170 and 14,500 nm. The determination of lichen transmittance is key in assessing the assumption that satellite reflectance measurements represent mixtures of lichen and rock reflectance linearly weighted by their respective surface cover. Therefore, the first aim of this paper is to report the estimation of transmittance of lichens in the 350–2500-nm region. We have selected this spectral range because of its relevance to many current airborne hyperspectral remote sensing systems. From the results, we propose that lichen essentially do not transmit light to their rock substrate and therefore effectively mask the mineral substrate. The second aim of this paper is to examine the variation in lichen spectra in association with colour, type, and species of lichen. From the results, we suggest a set of spectral indices to discriminate lichens and a set of spectral indices to guide the selection of a single lichen end-member for use in the SMA of rock and lichen.

2. Experimental approach

Lichen bearing rock samples were collected in June 1999 from the Gog Quartzite Formation in Jasper, Alberta, Canada (52°12′ N, 117°15′ W). The quartzite substrate is ideal for an investigation of lichen spectral properties because it provides uniformly high reflectance and mineral absorption features are well understood and likely discernable from that of lichen. The quartzite samples are compositionally homogenous and, therefore, show little spectral variation within samples and between samples. Twenty-seven lichen bearing rock samples were collected and measured within a 2-week period to ensure a healthy condition of the lichens. While not in use, the samples were stored in an outdoor, natural environment with direct sun, and exposed to wind and rain. Reflectance spectra were acquired from five different locations on each of the seventeen lichen patches under dry conditions, comprising a total of five different species (Table 1). The measurements were taken using a FieldSpec FR spectroradiometer, which operates in the 350–2500-nm spectral range and is characterized by a spectral resolution of 3 nm at 700 nm, 10 nm at 1500 nm, and 10 nm at 2100 nm (Analytical Spectral Devices, 2001). Measurements were recorded in reflectance mode (as opposed to radiance) as an average of forty scans in order to minimize instrument noise.

To assess the transmittance of lichens, measurements of reflectance were acquired on lichen samples that could be excised from the rock substrate without damaging or altering the lichen. Each foliose lichen sample was placed on a white Spectralon reference panel (99% reflectance) and measurements were recorded. The sample was subsequently placed on a black Spectralon reference panel (2% reflectance) and the spectrum was measured again. Each measurement was normalized to a bare 99% reflectance panel to calculate reflectance.

In order to measure pure patches of crustose and foliose lichen species, the field of view (FOV) of the spectroradiometer must be sufficiently small to preclude viewing a

Table 1
Lichen species investigated

Lichen species	Type	Colour	Number of patches	Total sample measured
U. torrefacta	Foliose	brown–black	5	25
R. bolanderi	Crustose	grey–black	3	15
R. geminatum	Crustose	black	2	10
R. geographicum	Crustose	green	2	10
A. cinerea	Crustose	grey–black	5	25

Species that were identified on at least two different rock samples were used. A total of 85 individual lichen measurements were used.

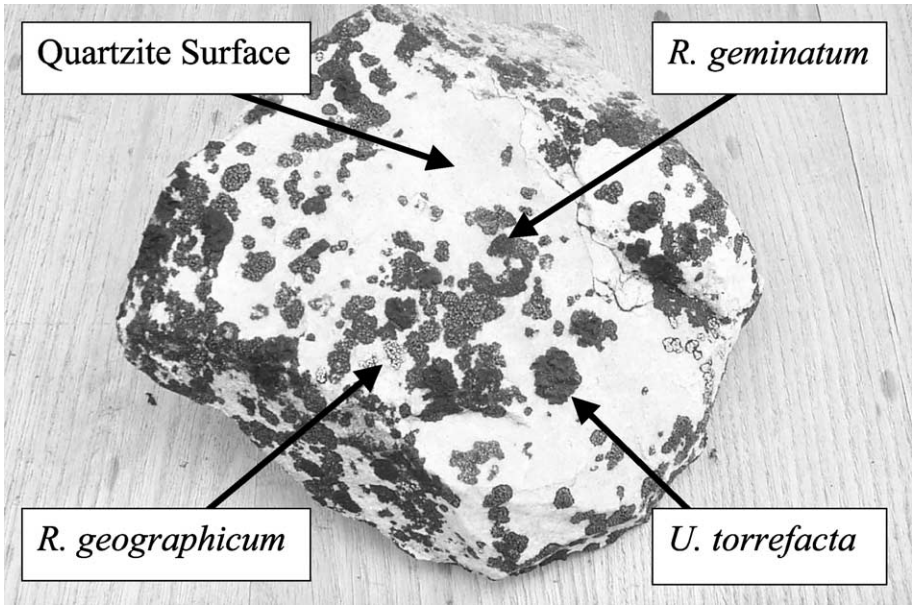

Fig. 1. Quartzite sample partly covered by crustose (*R. geographicum* and *R. geminatum*) and foliose (*U. torrefacta*) lichen. The sample has a width of 20 cm.

mixture of lichen and rock (Fig. 1). The FOV must also be sufficiently small to ensure that only a single species of lichen is being measured at a given time. For the lichen patches on our samples, a FOV of approximately 0.5 cm in diameter was required. This FOV condition was achieved by bringing a fiber optic (FOV 25°) into a position normal to the surface within 1 cm of the sample. The close proximity of the fiber optic to the sample implied a minimum angle of 35° from the zenith for the source of illumination to ensure the absence of a shadow in the FOV that would result from the tip of the fiber optic. For the experiments, two quartz halogen lamps of 50 W placed on opposite sides provided concurrent illumination from 0° to 180° azimuth. This measurement scenario was implemented to avoid the effect of shadows resulting from the microtopography of the sample. Reflectance spectra were obtained by determining the ratios of data acquired for a sample to data acquired for the 99% reflectance spectralon panel under the same illumination and observation conditions. Measurement of the natural targets took place within minutes of the standard panel measurement to minimize the effect of instrument drift.

3. Results

3.1. Spectral features of rock encrusting lichens

Dark coloured crustose and foliose lichens display a reflectance between 3% and 7% in the visible range. Both the grey–black crustose (e.g., *Aspicilia cinerea* and *Rhizocarpon bolanderi*) and the brown–black foliose (e.g., *U. torrefacta*) lichens exhibit a weak absorption feature at 685 nm attributed to the presence of chlorophyll (Fig. 2). This absorption is not seen in the spectra of *R. geminatum*, *R. geographicum* is a mosaic of tiny green 'tiles' (areoles) set against a distinctly black background (Johnson, Kershaw, MacKinnon, & Pojar, 1995). The green appearance of this lichen comes from the presence of these areoles, not from the lichen thallus itself. The reflectance is 4–5% at 400 nm and quickly rises to approximately 11–17% from 520 nm until the chlorophyll absorption at approximately 685 nm. *R. geographicum* shows a green peak at approximately 550 nm that is more characteristic of vascular plants than some of the darker coloured lichens. Dark coloured lichen species (brown, grey, and black) do not have a green peak in reflectance. All lichens sampled in this study had a gradual increase in reflectance to 1380 nm followed by an absorption feature centered near 1445 nm caused by water in the lichen. The spectra then display an increase in reflectance reaching a maximum value around 1860 nm. Beyond the water absorption feature near 1935 nm the spectra are similar in shape for all species investigated. All lichens display small within species variability as shown in Fig. 2.

Ager and Milton (1987) identified three broad absorption features near 1730, 2100, and 2300 nm, which are attributable to the presence of cellulose in lichen. These broad features are seen in the spectra shown on Fig. 2, but there are also other subtle features. Specifically, for most lichen species, the absorption at 1730 nm occurs with two other absorption features at approximately 1690 and 1770 nm. The 1770-nm feature is also attributable to cellulose (Fourty, Baret, Jacquemoud, Schmuck, & Verdebout, 1996) and its depth varies amongst species. A broad feature near 2300 nm is present in all lichens of this study but it encompasses two absorptions near 2300 and 2355 nm. However, an absorption feature at 2355 nm also appears in the quartzite spectra, and it therefore cannot be uniquely associated with lichen.

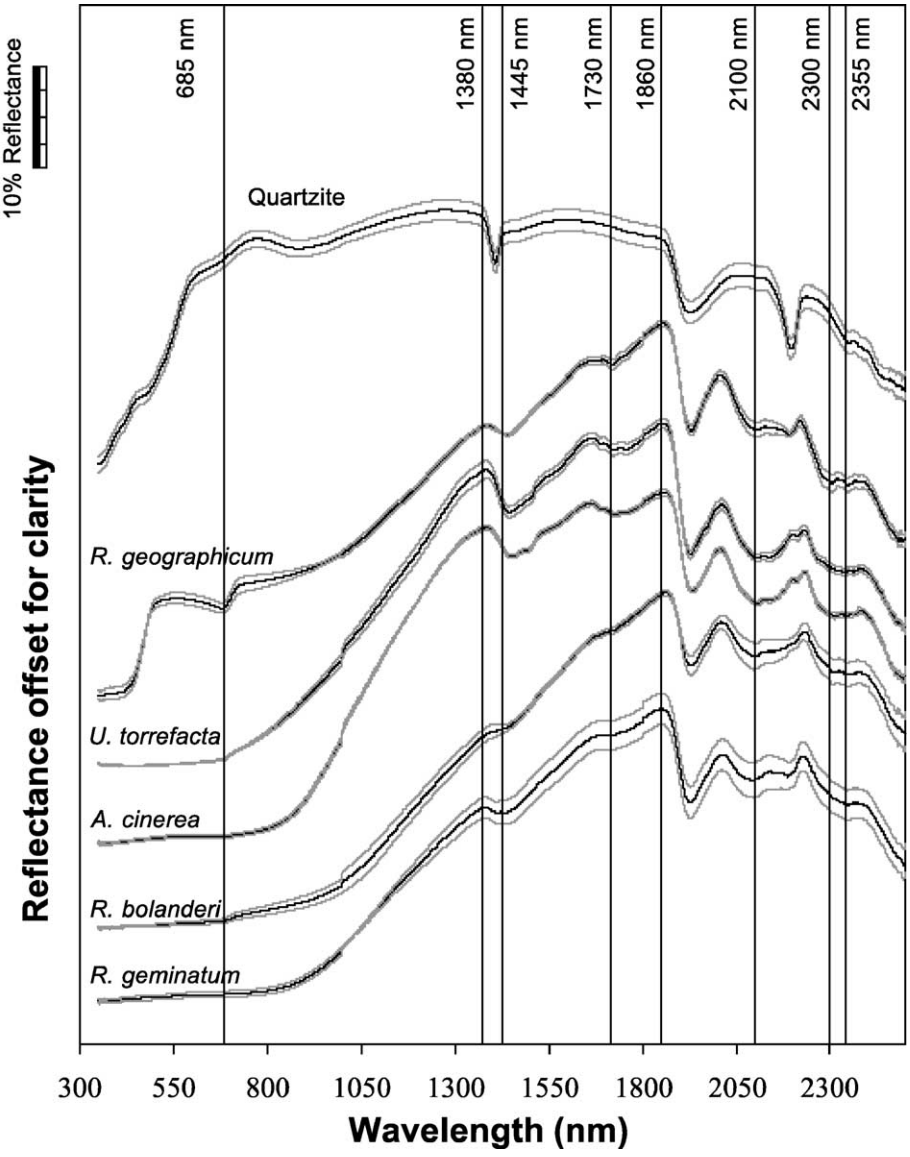

Fig. 2. Spectral characteristics of five lichen species and quartzite (350–2500 nm). Each spectrum is shown as a black line representing the average of five locations and is bound by ± 1 S.D. (gray lines). The vertical dashed lines mark the location of spectral features discussed in the text. Percent reflectance for *y*-axis is offset for clarity.

The specific feature near 2300 nm was not observed in foliose lichens and was weak or absent in some crustose lichens. Although the amplitude of the subtle absorption features can vary among species, the overall shape of the spectra is very similar, particularly between 2100 and 2400 nm. This characteristic spectral shape can provide the possibility to determine a representative spectral end-member for lichens that might be used to solve mixtures of lichen and rock.

3.2. Transmittance of light through lichen

Foliose lichen samples (*U. torrefacta*) were well suited to assess the transmittance of lichens. *Umbilicaria* are attached to the rock substrate by a single holdfast called an umbilicus (Johnson et al., 1995), which can be cut without affecting the exposed surface of the lichen. The area of the samples covered the entire field of view of the sensor and no gaps in the lichen thallus were visible. Five samples were selected which displayed a relatively flat surface to minimize microtopographic variations, which could influence the magnitude of the reflectance.

Reflectance spectra of *Umbilicaria* on 2% and 99% reflectance reference panels show only small differences in magnitude ranging from 0% to 3% (Fig. 3). The greatest difference is observed near spectral peaks at 1380, 1660, and 1860 nm (Fig. 3). The small difference in reflectance for the two different panels indicates that foliose lichens transmit little or no light. In fact, some of the observed minor differences between the two measurements could be largely

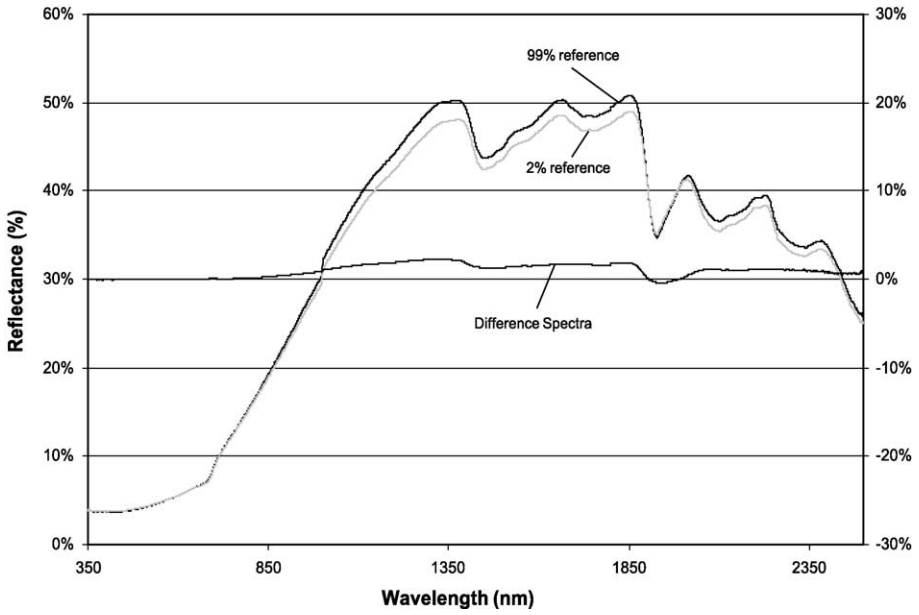

Fig. 3. Reflectance spectra of foliose lichen on 99% reference panel and 2% reference panel. Percent reflectance for the difference spectra (99 – 2%) is displayed on the right.

due to uncertainties in the sample alignment as it was moved from the white reference panel to the dark reference panel. An indication that this could be the case is that there are regions of the difference spectrum where the measurement for the dark panel has slightly higher reflectance than that of the white panel (e.g., at the bottom of the 1900-nm water absorption feature).

3.3. Discrimination of lichen species

For this study, a plot of the ratio of reflectance at 400/685 nm against 773/685 nm was used to isolate the spectral characteristics of different colours, types, and species of lichen. Wavelength bands selected are located in areas of the spectrum that are not influenced by water absorption features. The value of reflectance at the 400-nm wavelength was used because all lichens, regardless of colour or type, have a reflectance of < 7% at this wavelength (Fig. 2). This low reflectance may be due to the presence of usnic acid, which occurs in many lichen species and depresses the reflectance of lichen (Ager & Milton, 1987). Rock reflectance at this wavelength is often >30% and is helpful in distinguishing rock signatures from lichen signatures. The value of reflectance at the wavelength of 685 nm was utilized because it is assumed to represent the absorption that is associated with the presence of chlorophyll. A wavelength of 773 nm was chosen as the numerator because lichens have characteristically high reflectance at this wavelength yet show low variation between species. This is consistent with work by Gitelson, Buschmann, & Lichtenthaler (1999) who found that reflectance of plants was no longer dependant on the chlorophyll content past 750 nm.

Reflectance for the quartzite rock samples shows moderate values for the 400/685-nm ratio and distinctly low values for the 773/685-nm ratio (Fig. 4), which are distinct from that of the lichen. The foliose lichen (*U. torrefacta*) spans a relatively large range in Fig. 4, with high values for both ratios. The green crustose lichen (*R. geographicum*) forms a group that has low values for both ratios. The index also appears to discriminate species of lichens of the same colour and type as indicated by the ellipses on Fig. 4 that show measurements common to a given species or to the rock (quartzite). For example, *R. bolanderi*, a grey to black crustose lichen, has high values for the 400/685-nm ratio and moderate values for the 773/685-nm ratio. *R. geminatum*, another dark, black crustose lichen, has, however, high values for the 400/685-nm ratio, but lower values for the 773/685-nm ratio, forming a different group. *A. cinerea*, a greyish, black crustose lichen, assembles somewhere in between the *R. bolanderi* and the *R. geminatum*, with the 400/685-nm ratio ranging from high to mid values. *A. cinerea* appears anomalous because two samples plot in different locations than the other three samples of this species. The two anomalous samples came from the same rock sample and were identified as having a parasitic infestation. This may have led to an alteration in their spectral reflectance.

3.4. Discrimination of rock and lichen

Ager and Milton (1987) found that the reflectance of a group of lichens beyond 1400 nm differed by < 5%. Rivard and Arvidson (1992) reached similar conclusions though they were unable to quantify the similarities due to the

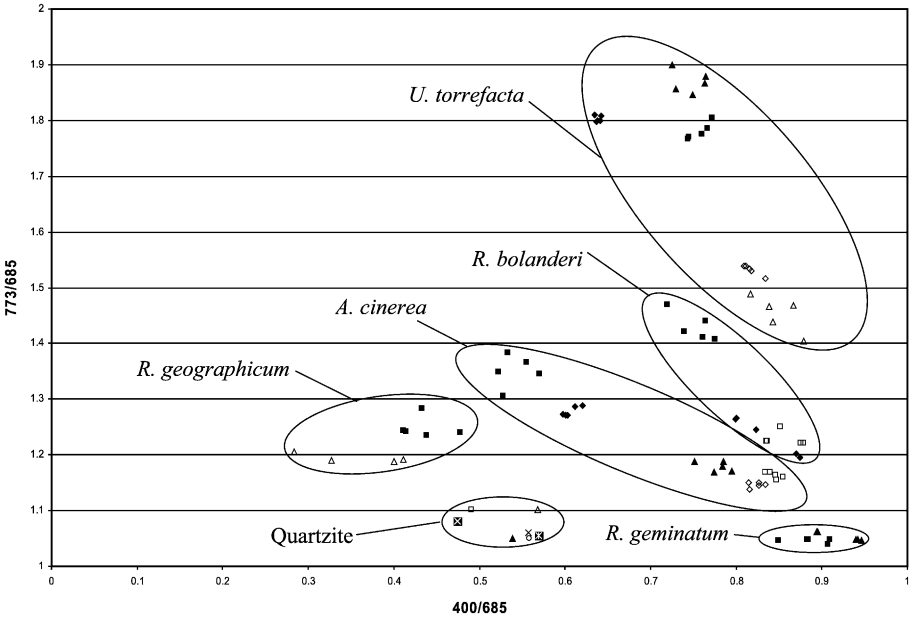

Fig. 4. Index 400/685 vs. 773/685 nm showing the separation of rock from lichen and the separation of different lichens species. Foliose lichens (*U. torrefacta*) are black in color. *R. bolanderi*, *A. cinerea*, and *R. geminatum* are grey–black crustose lichens. *R. geographicum* is a green crustose lichen. Five measurements from each lichen sample were taken and are separated from same species samples with different marker symbols. Ellipses encompass measurements common to a given species or for rock (quartzite).

potential contamination of their lichen spectra by the rock substrate. This study explored the possibility of using this similar spectral character to distinguish lichen from rock.

An index using the band ratios 2132/2198 and 2232/2198 nm outlines the similarity of lichen spectra in the infrared and a distinguishing feature between quartzite rock and lichen (Fig. 5). In silicate minerals, vibrational absorptions in the 2200–2400-nm wavelength region related to combination bands involving the hydroxyl ion (OH^-) fundamental stretching mode have been well documented in the literature (Clark, King, Klejwa, Swayze, & Vergo, 1990; Hunt, 1977; Hunt & Salisbury, 1970). The quartzite samples exhibit a strong OH^- related absorption feature centered near 2200 nm (Fig. 2). Reflectance at 2132 and 2232 nm were selected for the index because they represent spectral regions of high reflectance for this rock, which are located on each side of the diagnostic hydroxyl absorption feature centered near 2200 nm. In contrast, lichens display a

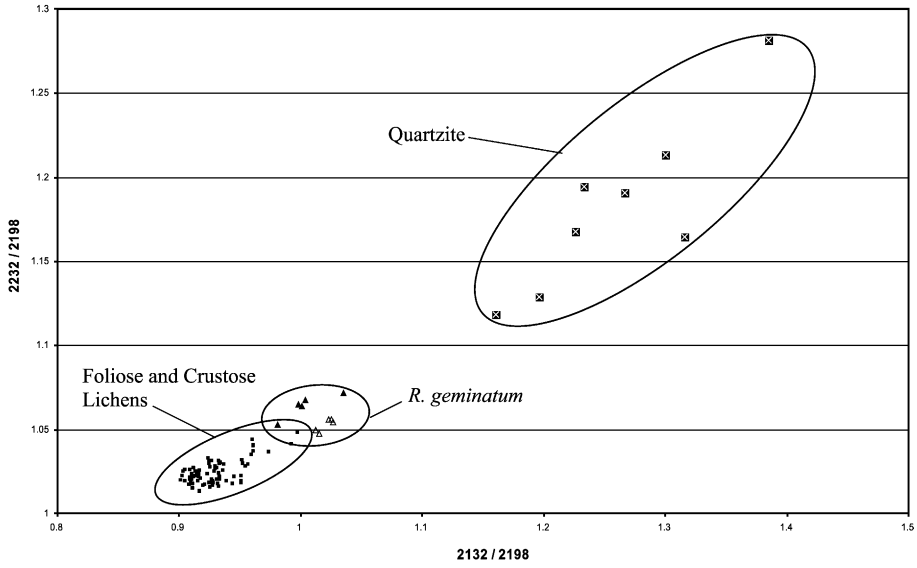

Fig. 5. Index 2132/2198 vs. 2232/2198 nm showing the separation of rock from lichen. Individual measurements of lichens are shown as black squares except for *R. geminatum*, which is shown as small triangles. Five measurements are shown for each lichen sample.

particularly strong reflectance peak (Ager & Milton, 1987) in this region that facilitates the use of a simple index for the discrimination of lichen from rock.

On Fig. 5, the majority of lichens cluster tightly in an area of low values for both ratios, whereas the rock signatures extend linearly from mid to high values. Variability in both ratios for the rock spectra reflects variability of the hydroxyl band depth. Spectra with greatest band depth display the largest ratios. The lichens, regardless of type (crustose or foliose), color, or speciation, tend to cluster, with the single exception of *R. geminatum*, which are located toward the rock end-member distribution, but does not overlap it. The appearance of the *R. geminatum* as a separate group has two possible explanations. *R. geminatum* could have a spectral shape unique from that of the other lichens of this study. Alternately, the *R. Geminatum* could have shrunk by means of being in a dry state differently from the other lichen samples, and allowed light transmittance between the fungal bodies. Mixing of lichen and rock in the FOV would thus result in a spectrum with ratio values distributed along a curvilinear array between pure lichen and pure rock. There is a suggestion from Fig. 5 that some measurements of foliose and crustose lichens with ratio values above that of the dominant data cluster can yet record the influence of rock interstitial to lichen. The remainder of the lichen data defines a common lichen signature characterized by a limited range of ratio values.

4. Discussion and conclusions

A key objective of this study was to determine the magnitude of light transmittance through rock encrusting lichens. The results have important implications for modeling lichen/rock mixed pixels in airborne and spaceborne hyperspectral data for the purpose of mineral mapping. For this study, a comparison of spectral measurements of excised foliose lichen on a 99% reference panel and a 2% reference panel indicates that foliose lichens transmit little or no light (between 0% and 3%). Unfortunately, the rock encrusting nature of crustose lichens has prevented a similar study from being performed, as removal of crustose lichens from rock substrate was not possible. However, the similarity in the overall spectral shape (in the longer wavelengths) of these lichens with that of foliose lichens (Figs. 2 and 5) suggests that crustose lichens also transmit little or no light. These findings support the use of linear mixture models for the deconvolution of lichen/rock mixtures because it shows that the optical thickness of lichen largely prevents the transmission of photons though the lichen mat. Therefore, the subpixel influence of lichen and rock within a scene can be considered linearly weighted.

Discrimination of lichen groups (crustose vs. foliose), colour, and species is made possible through the creation of a ratio of reflectance at 400/685 nm against 773/685 nm. It was found that different colours of lichen tend to plot in very distinct groups. This result was expected as the ratios exploit a chlorophyll absorption feature, which varies with pigmentation. The shape of the green peak in *R. geographicum*, a green, crustose lichen, is considerably more plant-like than the flat spectra associated with black crustose lichens. Also, the ratios were able to distinguish foliose lichen from crustose lichen, even though colouration between foliose types and some crustose types was very similar. Lichen samples of similar colour and type, but different species, can also be discriminated with these ratios. For example, three different species of grey to black crustose lichens (*R. geminatum*, *R. bolanderi*, and *A. cinerea*) were discriminated from one another. However, further measurements of the grey and black crustose lichen species are required to determine if the robustness of the proposed distinctions and provide statistical constraints to the fields delineating species spectral characteristics in Fig. 5. In fact, with the current data removal of the ellipses would limit the usefulness of this ratio for discriminating *A. cinerea* and *R. bolanderi*. The ratios also show separation of the quartzite substrate from all lichen samples.

Although it is possible to distinguish the three grey–black crustose species (*R. geminatum*, *R. bolanderi*, and *A. cinerea*) used in this experiment, it cannot be said that all lichen species can be distinguishable using this approach. A much larger sample of lichens, from various study sites, should be measured and compared using the ratio of reflectance at 400/685 nm against 773/685 nm. This would provide a better indication of the ability to separate lichens by species at these wavelengths. With the thousands of lichens species that exist (Hale, 1983), it is unclear how many species can be spectrally identified given that many species can only be distinguished based on variations in physical parameters (Price, 1994). Though this study has not involved measurement of nonphotosynthetic vegetation (NPV) (stems, litter, branches), a visual comparison with published spectra by Elvidge (1990) indicates that lichens should be clearly distinguished from NPV in the visible spectrum. An assessment of their separability using the 2132/2198- and 2232/2198-nm ratios would require a careful examination of digital data which is beyond the scope of this study.

The limited range of the 2132/2198- and 2232/2198-nm ratio values for rock encrusting lichens supports previous observations by Rivard and Arvidson (1992), who show such lichens tend to have similar spectral curves in the longer wavelengths. This ratio plots lichen samples into a tight group (Fig. 5) separate from quartzite rock samples, suggesting that a single representative lichen end-member can be defined to model lichen and rock mixtures. The results of this study have a significant implication in the analysis of satellite or airborne remote sensing imagery. Much of the analysis of hyperspectral data for geological application is based upon the detection and identification of important OH features that occur in minerals within the 2000–2400-nm range. This study reveals the similarity of

spectra for most foliose and crustose lichens species within this spectral range, which are distinct from those observed in OH bearing minerals. Thus spectral unmixing of rock and crustose/foliose lichens can be successfully accomplished using a single lichen end-member for this spectral range. The proposed infrared ratios applied to the analysis of hyperspectral data can provide a simple means to discriminate rock exposures with varying lichen abundances.

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