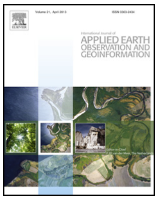
International Journal of Applied Earth Observation and Geoinformation 59 (2017) 1–8

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



Predicting the abundance of clays and quartz in oil sands using hyperspectral measurements

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ARTICLE INFO

Article history:
Received 17 January 2017
Accepted 21 February 2017

Keywords:
Oil sands
Clay minerals
Hyperspectral data
Infrared
Spectroscopy

ABSTRACT

Clay minerals play a crucial role in the processability of oil sands ores and in the management of tailings. An increase in fine content generally leads to a decrease in both bitumen recovery performance and tailings settling rate. It is thus important to identify clay types and their abundance in oil sands ores and tailings. This study made use of oil sands samples characterized for quantitative mineralogy by x-ray diffraction, to gain an understanding of changes in the reflectance spectra of oil sands. The sample suite included bitumen-removed oil sands ore samples and their different fine size fractions. Spectral metrics applicable to the prediction of quartz and clay contents in oil sands were then derived with a focus on metrics correlating with sample content in total 2:1 clays (total of illite and illite-smectite) and kaolinite. Metrics in the shortwave infrared (SWIR) and longwave infrared (LWIR) were found to correlate with mineral contents. The best predictions of clays and quartz were achieved using LWIR metrics ($R^2 > 0.89$). Results also demonstrated the applicability of LWIR metrics in the prediction of kaolinite and total 2:1 clays.

1. Introduction

Oil sands located in northern Alberta, Canada, contain a vast reserve of heavy oil. Alberta oil sands are natural mixtures comprised of 55–80 wt% minerals (primarily quartz and clays), 2–15 wt% water, and 4–18 wt% bitumen; a highly thick and viscous oil (Kasperski, 2001). Bitumen production through open-pit mining uses a water based process that results in production of large volumes of tailings; mixture of solids, water, and residual bitumen. Among the factors affecting the bitumen recovery efficiency, ore mineralogy plays a critical role. Silicates and phyllosilicates, sulfides and sulphates, oxides and hydroxides, phosphates, and carbonates, are the mineral classes found in Alberta's oil sands (Bichard, 1987; Hepler and Hsi, 1989). Clay minerals are particularly important, as a relationship exists between increased clay content in oil sands ore and decreased bitumen recovery (Liu et al., 2004). Kaolinite and illite have been observed to comprise a major fraction of clays in oil sands (Kessick, 1979; Kotlyar et al., 1995; Mercier et al., 2008). However, evidence of the presence of minor amounts of chlorite, vermiculite, smectite, and mixed layer clays including illite-smectite and kaolinite-smectite has been reported in several studies (Yong and Sethi, 1978; Scott et al., 1985; Omotoso and Mikula, 2004; Omotoso et al., 2006; Kaminsky, 2008). It has been reported that active clays, mainly interstratified and ultrafine illite and kaolinite, are responsible for poor bitumen recovery and slow settling of tailings (Kasongo et al., 2000; Wallace et al., 2004; Omotoso and Mikula, 2004). Consequently, characterization of the abundance and type of clay minerals is of importance to the oil sands industry due to their influence on ore processability and tailings operations.

Several techniques are employed for the characterization of minerals in oil sands. As summarized by Kaminsky (2008), energy-dispersive x-ray spectroscopy (EDX) analysis and x-ray fluorescence spectroscopy (XRF) are used to investigate elemental composition, electron diffraction (ED) and x-ray diffraction (XRD) are employed to determine the mineralogy, quantitative XRD (QXRD) methods are used to determine the quantitative content of minerals in the samples, and transmission and scanning optical and electron microscopy (TEM and SEM) techniques are used to study the morphology and interactions between minerals. These methods are time-consuming, expensive, and require extensive sample preparation prior to data collection and analysis.

Reflectance spectroscopy is a quick and reliable method widely used for mineral detection and quantification. Hyperspectral sen-

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http://dx.doi.org/10.1016/j.jag.2017.02.018
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Table 1
Minerals and their weight% fraction determined by QXRD for the oil sands samples.

Sample	Size Fraction (μm)	Quartz	K-feldspar	Kaolinite	Total 2:1 clays[b]	Chlorite	Carbonates[c]	TiO_2	Pyrite	Total clay content[d]
MC1[a]	Bulk	72.1	3.9	8.9	7.5	0.2	13.7	0.3	0.1	16.6
	<2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	0.2–2	16.4	1.3	38.4	33.7	1.2	10.0	0.0	0.0	73.3
	<0.2	15.9	3.4	21.5	40.8	1.1	13.7	0.2	0.2	63.4
EC1[a]	Bulk	52.3	2.7	14.4	25.3	1.3	3.3	0.7	0.0	41.0
	<2	4.2	1.0	28.9	58.9	4.6	2.1	0.3	0.0	92.4
	0.2–2	6.9	0.6	37.0	52.6	2.3	0.3	0.3	0.0	91.9
	<0.2	1.2	0.9	21.4	64.8	8.9	2.7	0.3	0.1	95.1
MC2	Bulk	51.7	3.8	11.7	17.8	0.0	14.1	0.2	0.2	29.5
	<2	6.6	0.9	36.7	52.4	0.0	2.9	0.5	0.0	89.1
	0.2–2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	<0.2	0.0	2.4	11.3	82.6	0.0	2.5	0.7	0.0	93.9
EC2	Bulk	62.9	2.0	12.2	20.2	0.0	2.3	0.4	0.0	32.4
	<2	12.4	1.1	28.7	55.9	0.0	0.0	1.2	0.0	84.6
	0.2–2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	<0.2	0.0	1.7	14.9	82.7	0.0	0.0	0.7	0.0	97.6

[a] The mineralogical and chemical composition of the samples MC1 and EC1 have been thoroughly investigated in Osacky et al. (2013a, 2013b).
[b] Total of illite and illite-smectite.
[c] Total of calcite, siderite, and dolomite.
[d] Total of kaolinite, total 2:1 clays, and chlorite.

sors measure the natural radiation reflected or emitted from the materials surface in narrow (typically < 10 nm) and contiguous spectral intervals across a wide portion of the electromagnetic spectrum (e.g. 400–2500 nm). The spectral response from each material is controlled by the chemical composition and crystal structure of the minerals and materials within, and is wavelength dependent. The spectroscopy of clay minerals has been investigated in several studies (e.g. Farmer and Russell, 1964; Oinuma and Hayashi, 1965; Clark et al., 1990; Salisbury et al., 1991; Gates, 2005; Bishop et al., 2008, 2011; Yitagesu et al., 2011). In general, clay minerals can be identified using characteristic absorption features caused by vibrations of the hydroxyl (OH) group and structural water molecules as well as vibrations involving silicon, oxygen, and octahedral, tetrahedral, and interlayer cations.

In our past research, we have explored the use of hyperspectral sensing to estimate several characteristics of oil sands ore and tailings (Rivard et al., 2010; Entezari et al., 2016, 2017). In this study, we make use of oil sands samples characterized for their quantitative mineralogy, obtained from QXRD (Osacky et al., 2013a, 2013b), to gain an understanding of changes in the reflectance spectra of oil sands with changes in mineralogy. The sample suite includes bitumen-removed oil sands ore samples (bulk samples; enriched in quartz) and their different fine size fractions (fine fraction samples; enriched in clay species). We then derive spectral metrics applicable to the prediction of quartz and clay contents in oil sands ore and tailings. Focus is given to defining the best spectral metrics correlating with sample content in total 2:1 clays (total of illite and illite-smectite) and kaolinite, as clays impact bitumen extraction and tailings treatment. In doing so, we aim to gain an insight in the ratio of swelling to non-swelling clays in oil sands ore and tailings. The ability to quickly analyze oil sands (ores and tailings) and assess their mineral content characteristics, in particular that of clay minerals, may allow for improved extraction processes and tailings management.

2. Materials, measurements, and methods

2.1. Sample description

Three sample suites were used in this study: 1) a suite of Dean-Stark extracted (bitumen-removed) oil sands samples with quantitative mineralogy that was obtained in a parallel study, 2) a suite of oil sands ore samples, and 3) a suite of oil sands tailings samples. Each sample suite is described in the section below. The first suite was used to define spectral metrics with the strongest correlation to mineral content (clays and quartz). The other two suites were used for investigating the applicability of the spectral metrics for the mineral characterization of ore and tailings.

2.1.1. Dean-Stark extracted oil sands samples with quantitative mineralogy

The quantitative mineralogy of four bitumen-removed oil sand ore samples (bulk samples) and their different size fractions (<2 μm, 0.2–2 μm, and <0.2 μm) was obtained from QXRD analysis (Table 1), a portion of these data was reported in Osacky et al. (2013a, 2013b). The ore samples were provided by a major oil sands company and collected from a mine in Alberta. The fine fraction (<0.2 μm) was isolated by techniques that included settling and centrifugation of solids suspended in water. The total 2:1 clays shown in Table 1 refer to the total of illite and illite-smectite interstratified clays, as QXRD cannot separately quantify the amount of illite and mixed layer clay minerals (Osacky et al., 2013b). Quartz and clay minerals constitute the major fraction of the samples. However, traces of K-feldspar, carbonates (calcite, dolomite, and siderite), pyrite and TiO_2 minerals are also observed. The total clay content generally increases with decreasing size fraction since clay minerals are typically aggregated in the clay size fraction (particle size <2 μm) of a soil or an ore.

The content in total clays and quartz are negatively correlated for all the samples (Fig. 1), consistent with the known trend for oil sands ore mineralogy. Also, the content in total clays and total 2:1 clays are positively correlated. Interestingly, the data patterns exhibited for the total clays versus kaolinite is more complex. There is a positive correlation observed for the bulk samples, but the fine fractions deviate from this trend and show a nearly negative correlation (Fig. 1c). Similarly, the content in kaolinite and total 2:1 clays are positively correlated for the bulk samples but negatively correlated for the fine fractions. This sample suite is thus well suited for the spectral investigation of this study because it displays a wide variation in quartz (0–72.1 wt%), total clays (16.6–97.6 wt%), total 2:1 clays (7.5–82.7 wt%), and kaolinite (8.9–38.4 wt%) content. Moreover, there are samples that are enriched in total 2:1 clays and depleted in kaolinite and vice versa. Thus one can investigate changes in reflectance spectra with varying abundances of these clay minerals.