Full Length Article

Quantification of organic content in shales via near-infrared imaging: Green River Formation

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HIGHLIGHTS

- Kerogen content of organic-rich shales is quantifiable from near-infrared images.
- Spectral models are developed for the thermally immature Green River Formation.
- Models are used to map organic content for an entire core at high resolution.
- Performance is compared to a previously developed optical method.

ARTICLE INFO

ABSTRACT

We demonstrate the applicability of near-infrared (NIR) imaging for quantifying the spatial distribution of kerogen content in organic-rich shales with sub-millimeter resolution over cores that can span hundreds of feet in depth. We develop models that are validated for the thermally immature oil shale of the Mahogany zone in the Green River Formation. They utilize either all or part of the NIR reflectance spectrum thereby providing some flexibility in the choice of instrumentation and, thus, cost. The models accurately recover fine-scale (sub-millimeter) variabilities in kerogen content from calibrations to a few coarse-scale (centimeter to meter) measurements, a process known as downscaling. This obviates slow, costly, and discrete fine-scale measurements in favor of a rapid, inexpensive, and continuous mapping approach. It also has implications for mapping thermo-hydro-mechanical properties of organic-rich shales, given that they strongly depend on kerogen content. Since our models utilize kerogen-specific absorption bands, they may also find use in other hydrocarbon-bearing source rocks.

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1. Introduction

Unconventional hydrocarbon resources such as oil and gas shale have recently emerged as major contributors to the global energy production [1]. Quantifying the organic content of these resources is not only important for their economic valuation but also development. Several methods exist in the literature: chemical analysis, pyrolysis, well logging, and spectroscopy [2]. This research focuses on spectroscopic methods, which are attractive due to their rapid-analysis, high-resolution, and non-destructive nature.

Spectroscopy consists of measuring the optical properties of a material, such as reflectance, for different wavelengths of light. Reflectance (R) is the fraction of the incident light intensity reflected from a surface. The graph of reflectance versus wavelength is called the reflectance spectrum. Vibrational and electronic processes at the molecular scale cause preferential absorption at specific wavelengths, which appear as dips or troughs in the reflectance spectrum [3,4]. These wavelengths are referred to as absorption bands and can be thought of as spectral fingerprints of the material. For substances that are mixtures of several components, the reflectance spectrum is the superposition of all component spectra. The more abundant a component the stronger its absorption bands appear in the mixture spectrum. Recent advances in the field of spectral imaging have allowed the acquisition of images, in which reflectance spectra are measured for each pixel in the image. The resultant data cube is referred to as a hyperspectral image [4].

Two regions in the infrared are commonly used in geosciences: (a) the mid-infrared (MIR; 2500–25,000 nm wavelengths) and (b) the near-infrared (NIR; 1000–2500 nm wavelengths). Absorption bands in the MIR are caused by fundamental vibrational modes of molecules, whereas NIR bands correspond to overtones and combinations of these modes [4]. Both are useful for quantifying mineral and organic abundances in geo-materials, but each has

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certain pros and cons. MIR bands are often well-separated and provide information about not only abundance but also molecular structure. However, instrumentation is more expensive [4]. NIR spectroscopy is rapid, cheaper, and requires minimal sample preparation making it ideal for spectral imaging [4,5]. Atmospheric gases also interfere less, which makes NIR better-suited for field deployment. Its disadvantage is that absorption bands overlap more compared to MIR requiring sophisticated data analysis techniques to extract useful information [4,5].

NIR spectroscopy has been the subject of much research for quantifying total bitumen content (TBC) in Athabasca oil sands. With a couple of band-pass filters, Thompson [6] showed that the ratio of reflectance at a non-bitumen-specific band (2180–2260 nm) to a bitumen-specific band (2270–2350 nm) correlates with TBC.[1] The accuracy of his method was later reported by [7] to be ±3 wt%. Shaw and Kratochvil [8] used NIR diffuse-reflectance spectroscopy to develop models that relate the first derivative of absorbance (=log (1/R)) to TBC. They identified 2285 nm, 2330 nm, 1725 nm, and 1760 nm as bitumen-specific bands. The models were used to map TBC along a 4-m core at a resolution and sampling interval of 1 cm. Interestingly, a high correlation coefficient (>0.75) between TBC and absorbance at all NIR wavelengths was observed. Donkor et al. [9] used a similar approach to map TBC for a longer 15 m core. Results were sensitive to surface roughness.

To increase model robustness and accuracy, Lyder et al. [7] analyzed oil sand spectra via two methods: Gaussian fitting and wavelet analysis. The Gaussian model utilizes absorption features at 2282 nm and 2532 nm, attributed to clay-bitumen and bitumen-atmosphere respectively, and the wavelet model relies on bitumen features at 2274 nm, 2396 nm, and 3725 nm. Model predictions were within 1–2 wt% TBC with the wavelet model being more robust. To allow applicability in real time (i.e., minimal data processing), Rivard et al. [10] developed broadband models that use reflectance at a few wavelengths only. Their "five-band" model is the most robust and utilizes absorption bands at 1754 nm, 2274 nm, 2396 nm, 2210 nm, and 2054 nm with errors 1.1–1.5 wt% TBC. The first three relate to bitumen, the fourth to clay, and the fifth to water. Speta et al. [11] applied this five-band model to hyperspectral images of several Athabasca cores.

Spectroscopic studies for quantifying total kerogen content (TKC) in shales are primarily focused on the MIR. Kerogen exhibits distinct aliphatic features at 3333 to 3571 nm wavelengths, which have little overlap with most minerals. Snyder et al. [12] showed that the intensity of alkyl bands in this region correlate well with TKC. Herron et al. [13] used a spectral unmixing method, which requires the addition of "kerogen standards" to a spectral library, to estimate mineralogy and TKC for a Green River oil shale core. Analysis times were ~15 min. Washburn et al. [14] used attenuated total reflectance (ATR)-Fourier Transform Infrared (FTIR) to map TKC over sub-millimeter scale areas of two Green River oil shale samples (Mahogany and R-6 zones, Piceance Basin). Automated sampling capabilities were used. Recently, field-based NIR imaging spectroscopy was used by Greenberger et al. [15] to identify oil-bearing strata in the Green River Formation. The study however did not attempt quantitative predictions of TKC.

This work examines the applicability of NIR imaging for quantifying the spatial distribution of TKC in organic-rich shales at sub-millimeter resolution over cores that can span hundreds of feet in depth. Most of the foregoing literature aims to develop models that can be robustly applied to new samples from different parts of a geologic formation. While this is partly the aim here as well, our main objective is to recover fine-scale variabilities of TKC from coarse-scale measurements (e.g., logs, pyrolysis): a process known as *downscaling*. Specifically, we develop NIR models that, when calibrated to a few coarse-scale measurements, can predict TKC at the fine scale. This is a key distinction from previous studies in that the goal is less to be predictive across samples than to be predictive across scales (of possibly the sample). This, with due caution, reduces the number of calibration data required and eliminates the need for potentially slow, costly, and discrete fine-scale TKC measurements (e.g., point or Rock-Eval pyrolysis) in favor of a rapid, cheap, and continuous mapping approach. It also has implications for mapping thermo-hydro-mechanical properties of shales, given they are often strong functions of TKC and its spatial distribution at the fine scale [16]. Maps of said rock properties can then be upscaled and served as inputs to field-scale simulators [17].

In Mehmani et al. [18], we developed an optical method that quantifies and downscales TKC for oil shale from the GRF. Its working principle is that darker samples correlate with higher TKC. While the method is very inexpensive, requiring optical photographs only, its accuracy deteriorates in the presence of interfering (dark-colored) minerals, e.g., clay. It is also less likely to be applicable to other oil/gas shale plays. Since NIR spectra contain kerogen-specific absorption bands, we hope this work provides a more direct, accurate, and potentially more general means of detecting and downscaling TKC.

Our analyses herein are confined to the Mahogany zone of the Green River Formation (GRF). The GRF is the largest known oil shale deposit worldwide with an estimated 4 trillion barrels of oil in-place [19]. Deposits are primarily concentrated in the Piceance Creek Basin in Colorado, the Uinta Basin in Utah, and the Greater Green River Basin in Wyoming [20]. The Mahogany zone is one of the richest geologic intervals within the GRF of the Uinta and Piceance basins and is thus of great economic interest [19]. Fischer Assay (FA) is the common unit of measurement for TKC in GRF oil shale and is defined as the gallons of extractable shale oil per ton of source rock (GPT). It is this parameter, which we aim to quantify herein. We analyze oil shale samples from both Colorado and Utah.

The paper is outlined as follows. Section 2 describes the lab and core samples studied. Section 3 details our methodology for developing NIR models predictive of TKC. In Section 4, we summarize the spectral models and compare their predictions against coarse- and fine-scale measurements. We discuss results in Sections 5 and summarize conclusions in Section 6.

2. Sample description

We analyze two sets of samples. The first corresponds to a core drilled in the Uinta Basin, Utah. The second consists of lab samples from the Piceance Creek Basin, Colorado. Both belong to the Mahogany zone in the GRF. Detailed sample descriptions were originally given in [18]. Below we provide a brief summary but mainly focus on new spectral measurements.

For each sample set, we identify and henceforth refer to *coarse-scale* measurements as those used to calibrate the spectral models developed in Section 3, and to *fine-scale* measurements as those used to validate them (i.e., their downscaling accuracy). The physical scale associated with the coarse- and fine-scale data is different for Utah (1 ft *vs.* 1–3 mm) and Colorado (2.5–4.8 cm *vs.* 6.5–9.5 mm) as detailed below.

2.1. Utah: Core samples

Skyline 16 and 12 are two adjacent wells, separated by ~10 ft, drilled and cored in 2010 on the eastern edge of the Uinta Basin, Utah, near the Douglas Creek Arch. Skyline 16 was drilled by the University of Utah and Utah Geologic Survey (UGS) [21], while Sky-

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[1] The original reference identified 2180–2260 nm as bitumen-specific and 2270–2350 nm as non-bitumen-specific. This is likely a typo as it does not agree with bands identified by others [8,10,11]. We have corrected this.