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Rapid determination of coalbed methane exploration target region utilizing hyperspectral remote sensing

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ABSTRACT

This study reveals the common surface mineral characteristics over coalbed methane (CBM) enrichment regions from spaceborne Hyperion images and the possibility of hyperspectral remote sensing for prospecting coalbed methane exploration target region with an inexpensive, large-scale, rapid and convenient way. For this study, a typical scheme including bands removal, atmospheric correction, SNR estimation, Minimum Noise Fraction (MNF), Pixel Purity Index (PPI) and n-dimensional visualization, was applied on Hyperion image in Qinshui Basin, China, to accurately extract mineral endmembers. The endmember spectra of carbonate and clay mineral were identified based on the diagnostic absorption feature, while no endmember of ferrous iron mineral was found. The absorption feature parameters of carbonate (absorption position and especially asymmetric factor) and clay mineral (absorption position, left and right shoulder positions) were quantitatively estimated, which showed the endmember spectra of carbonate and clay mineral from hyperspectral images in this paper were correct. In addition, this study proposed an interesting research direction: measuring the asymmetric absorption factor to facilitate the identification of carbonates. Furthermore, Spectral Angle Mapper (SAM) and Spectral Feature Fitting (SFF) were used to map carbonates and clay minerals. Two assessment methods, visual interpretation based on field spectra and X-ray diffraction (XRD) analysis, were utilized to evaluate the mapping accuracy, which showed total agreements of 84.03% and 72.58%, respectively. The results in this paper suggested that both carbonates and clay minerals were rich while there was hardly any ferrous iron mineral, on the surface of CBM enrichment regions. In addition, another similar experiment was carried out in Ordos Basin and also showed similar surface mineral characteristics on CBM enrichment region.

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1. Introduction

Coalbed methane (CBM) is considered as an unconventional gas resource which occurs in coal seam. The formation of CBM was either biogenically or thermogenically derived by producing CH_4 (the main chemical component of CBM) (Moore, 2012). Commercial production of CBM has made significant contribution to increasing the global energy resources and triggered the global activity in the area of CBM exploration (Clarkson, 2013; Salmachi and Yarmohammadtooski, 2015). Currently, conventional methods for the exploration of the CBM reservoir are principally core analysis, well-test analysis, geophysical logs, seismic methods etc. (Jiang et al., 2011; Wang et al., 2014). Although these methods can accurately extract the CBM reservoir parameters, they are highly costly and can only be used to explore CBM in a small-scale region. In addition, complex terrain in remote areas hinders the wide use of the existing approaches. In addition, a major problem of drilling is formation damage (Sircar, 2000).

Previous studies have demonstrated that a fair amount of oil–gas can migrate to the ground surface when reservoirs leak, resulting in geochemical alterations in soil and rocks (Van der Meer et al., 2002; Xu et al., 2008). The hydrocarbons in near-surface soils and sediments can be oxidized by microbial to produce CO_2, H_2S and organic acids, which can generate reducing and slightly acidic conditions. In these conditions, feldspars can be weathered to produce clay minerals. In addition, the oxidation of hydrocarbons can produce near-surface diagenetic carbonates as a byproduct following the chemical reaction (1). In the reducing conditions generated by hydrocarbons, ferric oxide was reduced to ferrous iron mineral following the chemical reactions (2)–(4) (Van der Meer et al., 2002).

$$C_nH_m + CaSO_4 \rightarrow CaCO_3 + CO_2 + H_2O + H_2S \quad (1)$$

$$C_nH_m + Fe_2O_3 \rightarrow Fe_3O_4 + FeO + CO_2 + H_2O \quad (2)$$

$$C_nH_m + Fe_2O_3 \rightarrow Fe_3SO_4 + FeCO_3 + H_2O \quad (3)$$

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$$C_nH_m + Fe_2O_3 \rightarrow Fe_3O_4 + FeCO_3 + H_2O \quad (4)$$

Hyperspectral remote sensing acquires images covering hundreds of square kilometer area in many narrow contiguous spectral bands (Magendran and Sanjeevi, 2014), and is a time and cost-efficient method to measure quantitatively the components of the Earth surface minerals from reflectance spectra (Mulder et al., 2013; Van der Meer et al., 2012). Hence, ferrous iron mineral, carbonate and clay mineral that are generally rich over the reservoir of oil–gas, can be detected successfully by hyperspectral remote sensing (Xu et al., 2008). Carbonate in this paper refers to carbonatite whose main components are minerals containing CO_3^{2-}. Hydrocarbon-induced alterations of carbonate include calcite, siderite, and magnesite (Van der Meer et al., 2002). As essential constituents of loam rocks, clay minerals are an important group of crystalline minerals, which can be classified into four main subgroup: kaolinite, smectites, illite, and chlorites. From the respect of chemical components, clay minerals are composed of aluminum silicate or a combination of iron and magnesium silicate, and some also contain alkaline earth. In oil and gas exploration, clay minerals are present in the targeting rocks (Karpinski and Szkodo, 2015). The main composition of CBM is also hydrocarbons (CH_4, a little of C_2, C_3, etc.) and migration is also present in the CBM reservoir. Thus, a hypothesis can be proposed that similar surface mineral characteristics (ferrous iron mineral, carbonate and clay mineral) may be present on the surface of CBM enrichment region. If the above hypothesis is true, hyperspectral remote sensing will make it possible to explore CBM in an inexpensive, large-scale, rapid and convenient way by mapping the hydrocarbon-induced mineral alterations, thus complementing the deficiencies of the aforementioned conventional CBM exploration methods.

For several decades, hyperspectral remote sensing has been used for mineral resource and energy source exploration. From the respect of mineral identification, in recent years, some scholars studied the diagnostic spectral absorption feature of carbonate and clay mineral, and mapped them successfully using hyperspectral remote sensing. For instance, the dolomite and calcite in southern West Greenland were mapped by the Self Organizing Maps (SOMs) using HyMap data (Bedini, 2009). Farooq and Govil (2014) detected Gossan (containing carbonates) from Hyperion image based on the Spectral Angle Mapper (SAM). Inversion of carbonate minerals from Hyperion data was also carried out by Percival et al. (2014) and Chen et al. (2013). Anne et al. (2014) proposed a spectral model to predict silt + clay using Hyperion data with a high accuracy. Bhattacharya et al. (2012) utilized Hyperion data for mapping clay minerals with Spectral Feature Fitting (SFF) and SAM. Carbonates and clay minerals related to hydrothermal alterations including calcite, kaolinite, and montmorillonite, were also mapped by Matched Filtering (MF) from HyMap image (Molan et al., 2014), and SAM and Mixture Tuned Matched Filtering (MTMF) from Hyperion image (Bishop et al., 2011). From the respect of application field, many researchers have carried out mineral mapping on hydrothermal systems that are rich in mineral resource utilizing hyperspectral remote sensing (Bedini et al., 2008; Crósta et al., 1998; Gersman et al., 2008; Kruse, 1988; Rowan et al., 2000; Sabins, 1999; Van Ruitenbeek et al., 2012). Lithologic mapping has also been studied using hyperspectral datasets (Chabrillat et al., 2000; Harris et al., 2005; Leverington, 2010; Magendran and Sanjeevi, 2014). What's more, some scholars proposed methods to use hyperspectral remote sensing to map the surface alteration rocks (ferrous iron mineral, carbonate, clay mineral) over oil–gas reservoirs (Van der Meer et al., 2002; Van der Werff et al., 2006; Xu et al., 2008). In coal geology, the main application of remote sensing and geographic information system is monitoring of coal fires, mine subsidence, environmental impacts of coal–mine closure and reclamation (Duzgun et al., 2011; Kuenzer et al., 2012). To the best of our knowledge, there is little information available in published literatures about mineral mapping on CBM enrichment regions for CBM exploration purpose using hyperspectral remote sensing.

For this study, we attempted to extract surface mineral characteristics on CBM enrichment regions by mineral mapping based on spaceborne Hyperion images, and to demonstrate the potential geological application ability of hyperspectral remote sensing for the determination of CBM exploration target region.

2. Geologic setting of study area

In this study, the southern part of Qinshui Basin, southeast of Shanxi Province, China, was investigated. The location and CBM content of this study area are shown in Fig. 1. The southern part of Qinshui Basin, with an area of 2922 km^2, has significant CBM potential and greatly deserves commercial CBM exploration (Wang et al., 2014). Clay, loam, sandstone and gravel (red-brown and earthy-yellow), are widely distributed in the Quaternary (Q) of this study area. Clay and sandy clay (celadon or sallow) in Neogene (N), outcrop between Jincheng and Gaoping. On the north of Jincheng and Yangcheng, west of Xiangyuan and Gaoping, the following formations outcrop widely: Shiqianfeng formation (P_2sh, aubergine sandstone and mudstone), Shangshihezi formation (P_2s, gray-white sandstone and aubergine mudstone), Xiashihezi formation (P_1x, tawny sandstone and manganese-iron ore), and Shanxi formation (P_1s, gray-white sandstone and gray-black clayish rock). In Taiyuan formation (C_3t), coal-deposit, sandstone, mudstone and limestone, outcrop on Jincheng, Qinshui and Yangcheng (Geologic Survey Report of Fanzhuang Exploration Area in Jincheng Mining District of Shanxi Province, 1993). Calcite (a type of carbonate) is the main component of limestone. Kaolinite and hydromica (two types of clay mineral) are the main components of mudstone. Hence, carbonates and clay minerals are widely distributed on the southern part of Hyperion image.

It has been proposed that there are five types of CBM reservoir boundary, such as hydrodynamic boundary, weathering oxidation belts, petrophysical property boundary, fault boundary, and lithological boundary (Su and Lin, 2009). As shown by Fig. 1, the CBM reservoir boundaries of the study area are the groundwater drainage divide (north, a hydrodynamic boundary), Sitou Fault (west), hydrodynamic boundaries (east and south). Fig. 1 also shows the contour line of CBM content in 3# coal seam, which illustrates the enrichment of CBM on the south part of the Hyperion image.

3. Hyperspectral image processing and analysis

In this study, the hyperspectral dataset was acquired by the spaceborne Hyperion sensor, a hyperspectral instrument on the EO-1 satellite, on March 20, 2013. The coverage area of the Hyperion image is shown in Fig. 1. Hyperion covers 220 unique spectral channels collected with a spectral range of 357–2576 nm at approximately 10 nm spectral resolution. In fact, there are only 198 calibrated bands (EO-1 User Guide Version 2.3, 2003). Because of an overlap between the visible-near infrared (VNIR) and shortwave infrared (SWIR) focal planes, only 196 bands were utilized in this study, bands 8–57 and 79–224. The overview technical flowchart of the proposed method is schematically shown in Fig. 2. First, the preprocessing of Hyperion dataset including bands removal, atmospheric correction and signal-to-noise ratio (SNR) estimation, is carried out to get a high-quality reflectance dataset for further analyses. Second, the endmembers are extracted from the Hyperion image. Third, the endmember spectra of carbonates and clay minerals are identified by the diagnostic absorption features. Finally, classification algorithms are utilized for the extraction of carbonates and clay minerals. The proposed method can be carried out with ENVI and IDL software.

3.1. Hyperion dataset preprocessing

In this paper, preprocessing of the Hyperion datasets consists of bands removal, atmospheric correction and SNR estimation. The bands eliminated in this study included water vapor absorption (bands 121–

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