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Research paper

Hyperspectral remote sensing for mapping and detection of Egyptian kaolin quality

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ABSTRACT

This study aims to use spectral analysis and hyperspectral Hyperion remote sensing images of the Egyptian Abu Zenima Carboniferous and Cretaceous kaolin deposits, located in West-Central Sinai Peninsula, for mapping the spatial distribution of their qualities determined by their mineralogical and geochemical parameters. Mineral quantification has been made by X-ray diffractometry and chemical analysis, and kaolinite structural order-disorder degree was measured by mean of the Hinckley (HI), Stoch (IK) and Liètard (R2) indices. The geochemical characteristics classified the studied samples into ferruginous and non-ferruginous deposits. The mineralogical composition discriminated the studied sample grades into kaolin (> 75% kaolinite), silty kaolin (75–50% kaolinite) and kaolinitic siltstone (< 50% kaolinite). Abu Zenima kaolin quality is mainly influenced by quartz and Fe-Ti minerals contents. The Carboniferous kaolin samples are characterized by ordered kaolinite (HI or R2 > 1 and IK < 0.7), while the Cretaceous kaolins exhibited mainly disordered kaolinite (HI or R2 < 1 and IK > 0.7). Five EO-1 Hyperion Level 1 GST radiometrically and geometrically corrected images of April and May 2011 were used to identify the spatial distribution of Carboniferous and Cretaceous kaolin grades and the structural characteristics of kaolinite. The position, depth, full-width-half-maximum and 22SP-Index of the absorption features were calculated for the continuum-removed spectra in the range 350–2500 nm. Prominent absorption features spectra occur around ~1400, ~1900, ~2200 and 2300 nm, and there are shifting and changes in their position and morphology with the kaolinite richness and the structural order-disorder degree. Spectral Angle Mapper (SAM) supervised classifications proved successfulness for identifying the kaolinite spatial distribution on the Hyperion images using the measured spectra of kaolins with different qualities and structural order-disorders.

1. Introduction

Kaolin is a fine usually white clay mainly made up of the clay mineral kaolinite and/or halloysite (> 75%; Kogel et al., 2006). It is a naturally abundant and inexpensive geomaterial and exhibits many various suitable properties that make it useful in numerous industrial, agricultural, civil, environmental and health-care applications (Ciullo, 1996; Murray, 1999; Carretero et al., 2013; Awad et al., 2017b). The remarkable kaolin resources are mined worldwide form giant districts located in the United States (the upper coastal plain areas of Georgia and south Carolina), Brazil (eastern Amazon region), the United Kingdom (Cornwall–Devon) and Germany (Bavaria and Saxony). However, numerous other significant kaolin occurrences, either exploited or not, are recorded in many countries of the world's continents except of Antarctica (Kogel et al., 2006).

According to the global statistical Mundi Index (2007), Egypt is the first kaolin producer in Africa and the Middle East, with the rank 19th worldwide (Ekosse, 2010). The total production of Egyptian kaolins in the last decade is about 3,702,000 metric tons, with an average of 375,000 metric tons per year, representing 1% of the worldwide production (Taib, 2015; Virta, 2015). Based on supply and demand of the local market of industrial minerals in Egypt, these deposits are essentially exploited, since the mid of the 20th century, as raw materials for ceramics, refractories, Portland cement, fillers, paints and paper

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industries (Abdel Shafy, 1967; Hegab et al., 1992; Rashed and Amer, 1994; Kamel et al., 1997). Awad et al. (2017a) have recently characterized some of the Egyptian kaolins, evaluating their mineralogical and chemical composition, purity, crystallinity, color, and rheology, trying to find alternative applications in health-care uses (i.e., pharmaceutical and cosmetic applications).

The grade and quality of economic kaolin deposits, as a raw material for industrial uses, are mainly determined on the basis of the kaolinite content and its structural order-disorder degree, as well as the associated quartz and Fe-Ti mineral impurities as mainly host of heavy metals (Vie et al., 2007; Teh et al., 2009; Gupta et al., 2011; Ptáček et al., 2013; Wardhana et al., 2014; Ndlovu et al., 2015).

Kaolin chemistry and mineralogy are normally affected by its genesis, from the source rock weathering, sediment transport till the depositional and diagenetic conditions, which have a strong influence on its physical properties such as color, opacity and whiteness, compactness, plasticity, and rheology, or its physicochemical properties, including sorption or cationic exchange capacities (Murray and Lyons, 1955, 1959; Vasilev et al., 1976; Cabrera and Eddleston, 1983; LaIglesia and Aznar, 1996; Fialips et al., 2000; Awad et al., 2017a).

The kaolinite structural order-disorder (i.e., the perfection degree of the phyllosilicate layers stacking) was calculated by first time by Hinckley (1963) who proposed an index (HI) that is considered as the most common. Beyond the HI, other six structural order indices were also introduced, including the QF index (Range and Weiss, 1969), the IK index (Stoch, 1974), the R2 index (Liétard, 1977), the H&B index (Hughes and Brown, 1979), the expert system (Plançon and Zacharie, 1990) and FWHM indices (Amigo et al., 1994).

The color spectrophotometric analysis (wavelength range from 400 to 700 nm) proved to be a helpful tool for discriminating mineralogical quality of kaolins, as strong relationships exist between the iron oxide contents and the CIE-lab chromatic and lightness parameters (Awad et al., 2017a). On the other hand, kaolinite and most of the mineral surfaces show diagnostic spectral signatures in Visible/Near Infrared (VNIR) and Shortwave Infrared (SWIR) of electromagnetic spectrum, which enables their detection (Hunt, 1977; Clark et al., 1990; Rowan et al., 2003; Kruse et al., 2006). Absorption features at specific wavelengths result from both, electronic and vibrational processes in molecules (Hunt and Salisbury, 1970, 1971), and they are caused by electronic processes that generally occur at wavelengths $< 1\,\mu m$ (VNIR spectrum), whereas the vibrational process occurs at wavelengths $> 0.94\,\mu m$ (SWIR spectrum, Hunt, 1977). Mineral absorption features are usually generated by the overtone or the combination of fundamental and overtone transitions of the vibrations of atom bonds. Absorption features at ~1400 nm and 2200 to 2400 nm are used in the identification of hydroxylated minerals, while minerals with absorption features at ~1910 nm and 2200 to 2400 nm are likely hydrated minerals. Minerals with three absorption features at ~1400 nm, ~1910 nm and 2200 to 2400 nm are usually identified as hydrated phyllosilicates (Poulet et al., 2005; Mustard et al., 2008). For example, clay minerals (like kaolinite, illite, and montmorillonite) have an absorption peak around 2206 nm, corresponding to the combination of(OH) stretch and Al-OH bending modes (Goetz, 1992; Kruse et al., 1993), and carbonate minerals (e.g. calcite) has an absorption peak around 2348 nm corresponding to CO_3 overtone vibrations (Gaffey, 1986). Spectral analysis of clay minerals indicated that their absorption features shift due to variations in composition and crystal structure (Kruse and Hauff, 1991; Hauff, 1991). Zhang et al. (2001) reported that the SWIR reflectance spectroscopy is capable of detecting clay minerals at abundances as low as 1 wt% and quantitatively estimating the structural order-disorder of kaolinite by defining a "14Sp Index" (calculated as A-B/A), where A and B correspond to the depths of the absorption feature doubled found around 1400 nm on the kaolinite spectra. Hyperspectral sensors acquire simultaneously images of the Earth surface in tens to hundreds of narrow spectral bands in such a way that a complete spectral pattern of each pixel can be derived for target detection, discrimination and classification (Kerekes and Baum, 2003).

Remote sensing techniques have been widely and successfully used for geological mapping and mineral exploration for decades (Goetz and Strivastava, 1985; Sultan et al., 1986; Boardman and Kruse, 1994; Rowan and Mars, 2003; Perry, 2004; Zhang et al., 2007; Amer et al., 2010; Amer et al., 2012a, 2012b, 2015; Pour and Hashim, 2011, 2012). The Hyperion hyperspectral images were used for several surface mineral mapping with significant accuracy (Jafari and Lewis, 2012; Kusuma et al., 2012; Farifteh et al., 2013).

With these premises and for an optimum valorization, it could be an interesting objective to functionalize the mineralogical and geochemical aspects integrated with hyperspectral parameters for discriminating grades of kaolin deposits (kaolinite richness and structural order-disorder), on regional scale occurrences, by means of the reconnaissance satellite imageries. Hence, the aim of this study is to use the measurements of VNIR and SWIR reflectance and Hyperion imagery with mineralogical and geochemical data to evaluate the usefulness of remote sensing techniques in mapping and detecting the kaolin purity and kaolinite structural order of the Egyptian Abu Zenima kaolin deposits. The proposed methodologies were applied on six lithological sections, located at Abu Zenima district, and related to different geologic formations and ages. The results could be also used as local and regional model for prospecting the high purity kaolin zones in the outcropped relevant bearing rock units.

2. Study site and geologic setting

Abu Zenima sedimentary kaolin resource, located between longitude 33° 14′ 00″ and 33° 24′ 00″ E and latitude 28° 52′ 00″ and 29° 10′ 00″ N at West-Central Sinai Peninsula, is one of the greatest reserve of economic interest in Egypt. It represents the highest quality amongst all the Egyptian kaolins and recorded by 120 million tons (Abd El Razek, 1994). The sedimentary basin of Abu Zenima district covers about 333 km^2 of cultivated and accessible lands, generally elevated up to 680–1000 m above sea level. The major outcrops of kaolin-bearing rocks at Abu Zenima district are exposed at Wadi Khaboba (K) and Gabal Hazbar (H) areas, located to the northern part of Abu Zenima district, and Wadi Abu Natash (N), Farsh El Ghozlan (F), Wadi Budra (B) and Gabal El Dehessa (D) sites, located to the South (Fig. 1).

The stratigraphic succession of the studied Abu Zenima district is ranged from the basement Pre-Cambrian rocks till the Quaternary deposits. The Pre-Cambrian basement rocks are considered as probable sources of the studied sedimentary kaolin deposits (Baioumy et al., 2012; Baioumy, 2014a, 2014b). These are mainly included by metamorphic schists, gneisses and migmatites, dark amphibolitic xenoliths of dioritic to quartz dioritic rocks and old granitoids intruded by younger pink granites and variable composition sets of dykes. The sediments were intruded by Triassic dolerite sills scattered in the central and southern portions of the area. The successions at the northern region were generally extruded by Miocene basaltic dykes with a main trend NE-SW direction (El Aref et al., 1988; Abdel Karim, 1996). The kaolin-bearing member at the studied Wadi Khaboba, Gabal Hazbar and Wadi Abu Natash sections is related to the Abu Thora Formation, with a the Lower Carboniferous (Visean) age (Kora, 1989, 1995). The kaolin-bearing member exposed at Gabal El Dehessa, Farsh El Ghozlan and Wadi Budra belongs to the Malha Formation, with a the Lower Cretaceous (Albian) age (Abdallah et al., 1963; Saied, 1990). Fig. 2 summarizes the lithology of the studied sections and location of studied samples. Lithology was described in detail in Awad et al. (2017a).

3. Materials and methods

Twenty-nine rock samples were collected from the Carboniferous outcrops, and thirty-six samples were collected from the Lower Cretaceous ones. The methods used for chemical composition, mineral identification and quantification were explained in Awad et al. (2017a).