Estimation of surface iron oxide abundance with suppression of grain size and topography effects

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A B S T R A C T

Mineral forms of iron oxide, such as hematite, goethite and jarosite, are important because they are widely distributed at the Earth's surface and because they are used as indicators for mineral exploration. Iron oxide abundance in rocks containing these minerals can be estimated from the absorption depth at wavelengths of around 900 nm in a reflectance spectrum, but this depth is also affected by extraneous factors such as grain size and topography. This paper investigated the effect of grain size on reflectance spectra and proposed a method for estimating iron oxide abundance in surface rocks by using remotely sensed data with suppression of the effects of grain size and topography. Reflectance spectra were measured in a laboratory from rock powder samples of different grain sizes containing iron oxide minerals. While the reflectance increased with decreasing grain size, the presence of ferric iron caused the absorption depth to be almost constant at around 900 nm, irrespective of the chemical composition of the sample. In addition, the difference between the reflectance at 550 nm and 760 nm (Slope) was a function of grain size. Iron oxide abundance can be estimated accurately by MCR-900D, which is the maximum absorption depth at the absorption center after the effect of grain size and topography was suppressed by Slope and the continuum-removal method, which takes the ratio between the original spectrum and its continuum, respectively. Correlation of MCR-900D results with datasets of actual spectral and chemical iron oxide laboratory measurements revealed that the mineral forms also need to be considered. MCR-900D results were significantly correlated with rock samples classified as containing different forms of iron oxide minerals (hematite, goethite and jarosite). Finally, MCR-900D was applied to an AVIRIS dataset for the Cuprite site in Nevada, USA. The results represented the enrichment zones of iron oxide within hydrothermally altered areas.

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1. Introduction

Mineral forms of iron oxide, such as hematite, goethite and jarosite, are widely distributed at the Earth's surface. The presence of ferric iron in these minerals means that they have three diagnostic absorption features in the visible to near-infrared (VNIR) regions; they exhibit charge transfer absorption between 480 and 550 nm, and crystal-field absorption between 630 and 715 nm, and between 850 and 1000 nm (Morris et al., 1985). These spectral features can be used to identify and distinguish between iron oxide minerals. This study considered iron oxide minerals to include hematite (α-Fe$_2$O$_3$), goethite (α-FeOOH) and jarosite (KFe$_3$(SO$_4$)$_2$(OH)$_6$).

In addition, iron oxide (i.e., ferric oxide or Fe$_2$O$_3$) abundance was considered to include iron oxyhydroxide (FeO(OH)) abundance, which is typically measured as Fe$_2$O$_3$ in chemical analysis. Most of the studies conducted on these spectral reflectance characteristics to date have been performed in laboratories (Morris et al., 1985; Sherman and Waite, 1985). Studies conducted in the field have shown that iron oxide minerals are not randomly distributed, but that they occur in zones associated with ore deposits (e.g., around ore bodies of porphyry copper deposits) (Townsend, 1987). Consequently, if the distribution of iron oxide minerals is associated with certain ore minerals (Gustafson and Hunt, 1975; Saegart et al., 1974), then locating minerals containing iron oxide can be used to identify sites that may be suitable for mineral exploration (Ciampalini et al., 2013).

In the field of planetary science, remote sensing data has been used to estimate FeO abundance. Iron exists as ferrous oxide on the surface of the moon and as ferric oxide on the Earth. Lucey

et al. (1998) estimated the FeO content of areas on the lunar surface after suppressing space weathering effects. On the other hand, the quantitative estimation of ferric iron oxide abundance on the Earth's surface by remote sensing is still in the initial stages. Fe_2O_3 is the most common iron oxide, and its abundance affects the depth for absorption features between 850 and 1000 nm (Cudahy and Ramanaidou, 1992; Hunt and Ashley, 1979). However, since the spectral reflectance of rocks and minerals in remote sensing data is also affected by factors such as chemical composition, topography, mixing and grain size (Murphy and Monteiro, 2013), these factors can affect the absorption depth, which is defined as the difference between the minimum reflectance of an absorption and a reflectance at the same wavelength on the straight line connecting two shoulders on the both sides of an absorption. Given the complexity of the interactions among these factors, their relative contribution to estimates of iron oxide abundance is typically not considered; however, we consider they would amount to several wt%.

Previous studies that have attempted to infer iron oxide abundance based on the reflectance spectra of surface rocks and/or rock samples have typically employed band ratios to suppress the effect of topography. For example, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) band4/band3 is used for estimating iron oxide abundance, and ASTER band2/band1 is used for classifying iron oxide forms (Cudahy, 2012). The band ratio is effective for removing the effect of topography; however, when the slope of the reflectance values of two spectral bands changes due to other effects, such as water content, organic material or grain size, using band ratios is not effective for removing the effect of topography (Murphy and Monteiro, 2013). Although Haest et al. (2012) managed to suppress the contribution of brightness by using reflectance at 1650 nm, which was assumed to be a function of brightness, reflectance at that wavelength would also be affected by the mineral composition and topography. The continuum-removal method (Clark and Roush, 1984) is a powerful pre-processing procedure that enhances absorptions in reflectance spectra in order to accurately identify minerals, rocks and vegetation (e.g., Gomez et al., 2008; Oshigami et al., 2013; Schmidt and Skidmore, 2003). In addition, the method is well suited to identifying minerals and rocks, particularly since the processed spectra are not affected by topography. However, the absorption depth for minerals identified using data processed with the continuum-removal method increases with increasing grain size (Clark, 1999). There are thus no established methods for estimating iron oxide abundance in remote sensing data that can suppress the contribution of grain size and topography.

The primary objective of this study was therefore to develop a method for estimating iron oxide abundance in surface rocks while suppressing the effects of grain size and topography. Accurate estimates of iron oxide abundance are necessary, not only to characterize the geology of an area of interest, but also because iron oxide abundance is used as an indicator of various ore deposits in exploration geology.

Reflectance spectra of samples containing iron oxides were collected, and the relation between grain size and absorption depths at around 900 nm due to iron oxides were investigated in the laboratory. The absorption depth was corrected by the continuum-removal method and the slope of the reflectance spectrum from 550 to 760 nm was plotted to suppress the topography and grain size effect, respectively. The relations between the absorption depths and iron oxide abundance were then established for three iron oxide minerals, and these relations were then applied to actual airborne image data of Cuprite, Nevada, USA obtained by AVIRIS. We discussed the effectiveness of our method for suppressing the grain size and topography effect when estimating iron oxide abundance.

2. Approach

2.1. Absorption depth

The absorption depth for rocks and minerals in this study was obtained by subtracting the continuum of a spectrum from the original spectrum to obtain a normalized absorption depth. The continuum is a convex background that decreases toward the shorter and longer wavelength regions, and can be drawn as a straight line on the reflectance spectra of iron oxide minerals in the region from 760 nm to 1250 nm. Thus, 900D, which is the maximum absorption depth between 850 and 1000 nm, can be calculated using the following equation:

$$900D = 900C - 900R \tag{1}$$

where 900C is a continuum value of a spectrum at approximately 900 nm, and 900R is the original spectral reflectance at around 900 nm. We assumed that the continuum represents the slopes of absorption values centered outside the 900 nm region due to other chemical components. In this way, the continuum-removal method would allow us to examine absorption by iron oxide only centered at around 900 nm.

In order to suppress the effects of grain size and topography, we introduced two absorption depths modified from 900D. CR-900D stands for Continuum-Removed 900D and indicates an absorption depth obtained from the reflectance spectrum after suppression of the topography effect by the continuum-removal method. MCR-900D stands for Modified CR-900D and indicates an absorption depth obtained from the reflectance spectrum after suppression of the effects of grain size and topography by the slope and the continuum-removal methods, respectively. The methods for calculating CR-900D and MCR-900D are explained in the following sections.

2.2. Topographic correction

At wavelengths longer than 550 nm, spectral reflectance increases at a constant rate as grain size decreases, but 900D does not change. In other words, differences in the reflectance values of samples with two different grain sizes are constant in this wavelength region. On the other hand, topography changes both spectral reflectance and 900D. The spectral reflectance of minerals and rocks is multiplicatively affected by topographic slopes (Green and Craig, 1985). If a the topographic slope is assumed to be $\tilde{a}$, then the topography effect is indicated as $T(\tilde{a})$ (e.g., $T(\tilde{a}) = \cos^2\tilde{a}$). The apparent reflectance with the topography effect ($Rtopo$) can be expressed by the following equation:

$$Rtopo = R \times T(\tilde{a}) \tag{2}$$

where R is the original spectral reflectance, and $T(\tilde{a})$ affects the spectral reflectance in all wavelength regions at a constant ratio regardless of the material in a pixel.

The continuum-removal method of Clark and Roush (1984) can then be applied to suppress the effect of topography. A continuum-removed spectrum can be derived by dividing an original spectrum (R) by its continuum (C), and the absorption depth due to ferric iron can generally be obtained by the following equation:

$$CR\text{-}900D = 1.0 - 900R/900C \tag{3}$$

where CR-900D is the absorption depth at an absorption center around 900 nm formed by ferric iron in a continuum-removed spectrum, 900R is the original spectral reflectance at the absorption center of the original spectrum, and 900C is the continuum value of the original spectrum at the absorption center in the wavelength region of 760 nm to 1250 nm. The CR-900D value of 0.0 means that the