Per-pixel and sub-pixel mapping of alteration minerals associated with geothermal systems using ASTER SWIR data

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Abstract. This paper is focused on assessing the applicability of the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) shortwave infrared data in proxy mapping of subtle geothermal (GT) systems by identifying hydrothermally altered indicator minerals. The study was carried out at Yankari Park NE Nigeria. Spectral mapping is applied on ASTER data using per-pixel and sub-pixel algorithms to extract and discriminate associated altered areas of interest. Field checks and altered rock sampling was done using GPS around the Wikki and Mawulgo thermal springs to validate results. Sampling points were used as training sites for image spectral analysis. X-Ray Diffraction results shows presence of kaolinite, quartz, hematite and dickite. This investigation demonstrates the utility of alteration mapping as a tool for GT resource exploration in uncharted regions.

1. Introduction

The use of remote sensing in the prefeasibility stages of geothermal (GT) prospecting has become imperative due to its synoptic capabilities and cost-effectiveness despite the challenges which hinders its use. This underscores the need for more exploratory research to assess and evaluate the applicability of satellite sensors especially in previously unmapped regions in order to develop improved methods and techniques of identifying such systems with their unique and peculiar characteristics. The most significant objective in the initial stages of either a mineral or a geothermal exploration using associated minerals as proxy, is the identification of areas of hydrothermal alteration. Hydrothermally altered rocks and their pattern of distribution can serve as a clue for locating geothermal systems [1]. Hot springs, geysers and fumaroles are obvious surface manifestations of GT activity which represent an integrated system of water, heat and rocks [1]. Identifying the locations of these features can aid the exploration of GT systems. Mapping of hydrothermally modified rocks has been made conceivable with the utilization of sensors that can distinguish spectral reflectance features of altered minerals noticeable within the visible near infrared to short wave infrared (VNIR-SWIR) portions of the electromagnetic spectrum [2]. Using the properties of reflected radiation, minerals altered or precipitated by hydrothermal waters can display diagnostic spectral absorption features from 400nm to 2500nm [2]. This makes it possible for their identification using remote sensing data. The ASTER sensor aboard the Earth observation system satellite detects radiation using 14 spectral bands[3]. ASTER is robust for mapping specific alteration
assemblages due to its enhanced spectral accuracy in the SWIR region [3] (see figure 1). This is a spectral region where many clay, carbonate and sulfate minerals (alteration indicators) manifest unique spectral signatures [4], as against the 2 SWIR bands in Landsat 7 (ETM+) and Landsat 8 (OLI). The improved spectral resolution provided by ASTER, makes it possible for identification of specific alteration assemblages [5]. The improved spectral characteristics of ASTER data in the visible, short wave and thermal infrared portion has made it suitable for geological studies through alteration mapping. Consequently, several studies have been done using ASTER [5].

The aim of this paper is to assess the ASTER (SWIR) data and perpixel/subpixel algorithms for mapping hydrothermal alteration zones related to GT systems as a tool for indirect identifications of prospects, specifically thermal springs using alteration mapping.

![Laboratory Spectra Resampled To ASTER Bandpasses](image)

**Figure 1.** Spectral reflectance characteristics of important hydrothermal alteration minerals resampled to ASTER band passes [4]

The Yankari Park is situated at Latitude 9.70°N, and Longitude 10.50°E in the state of Bauchi, NE Nigeria, it is an unexplored sparsely vegetated savanna region characterized by numerous thermal hotsprings such as; Gwana, Dimmil and the studied Mawulgo and Wikki. Field and GPS surveys conducted have indicated several hydrothermally altered rocks at sampled surroundings of the Wikki & Mawulgo.
The geology of Yankari Park is stratigraphically inside the Kerri-Kerri sedimentary region portrayed by Neogene to Mesozoic rocks which is made out of sandstones, siltstone and kaolinite-clays of Eocene age [6]. It is also part of the Benue Trough, circumscribed toward the west by the older granites of Jurassic age and Precambrian complex rocks of the Jos Plateau, and towards the northeast and southeast by the Biu and Adamawa highlands respectively. The land mass of Nigeria is viewed as an aseismic intra-plate, consequently structurally steady, notwithstanding, historical records showed that minor crustal instability have happened over the most recent 50 years in various areas [6]. Figure 2 shows Nigeria’s geology and location of Yankari Park.

2. Materials
In this investigation, a cloud free ASTER Level 1T scene covering the study area within Latitude 9.75000N, and Longitude 10.5000E (path/row, 187/53) was obtained from the LPDAAC data pool. The geometrically and terrain corrected image was first layer stacked in ENVI 5.1 software to form a data cube. The image is then adjusted and atmospherically corrected to compensate for atmospheric attenuations and other instrumental defects using the Log Residuals (LR) correction algorithm [7]. The LR algorithm was selected for its ability to produce a pseudo reflectance image best suited for diagnostic mineral reflectance recognition [8]. A 915 x 1122 pixels subset of the ASTER scene is created covering field sampled areas of the Mawulgo and Wikki thermal springs and their surroundings. A Regions of interest (ROIs) is selected using the ROI tool in ENVI. The ROIs is selected based on the GPS field validation waypoint location coordinates mapped during survey at the study area of Yankari Park in August, 2016. The regions are at the Wikki and Mawulgo thermal springs and the surroundings between them where hydrothermal alteration rock samples were obtained for laboratory X-Ray Diffraction. The pixel locator in ENVI was then used to identify the representative point designated M2 using the GPS coordinates acquired in the field during survey which are also areas where exposed hydrothermally altered rock samples were collected.
3. Methods

In this study, the Per-pixel; spectral angle mapper-SAM and Sub-pixel; linear spectral unmixing-LSU algorithms are used to Map hydrothermal alteration zones. SAM is a perpixel mapping technique which measures the similarity between an unknown spectra and a reference spectra by estimating the angle between the two spectra by processing the spectra as vectors in n-dimensional space. The reference spectra are usually sourced from spectral libraries [8], as in the case of this study, the ASTER library [8] (see Figure 3).

Figure 3. Reference endmember collection spectra from USGS library employed for analysis

Figure 4. ASTER RGB band 3, 2, 1 showing field sampling points, rock samples and spectral profiles at M2 (GPS coordinate: N9° 51. 067', E10° 30.748') proximate area NW of Mawulgo thermal spring
Three endmember spectra; illite, kaolinite and muscovite are selected from the ASTER library which are employed for discrimination of argillically altered zones as exhibited by clay minerals. The region of interest namely \textbf{M2} which is an area identified in the field with hydrothermally altered clay and where rock samples for XRD are obtained are used as regions of interest (ROIs) for the analysis [9]. The SAM and LSU is thus used at ROI \textbf{M2} to discriminate these pixels and show the abundance of the targeted argillic alteration minerals as indicators of GT activity. The LSU method relies on the linear mixture model in which it is assumed that the spectrum within a mixed pixel is a combination of the fraction of spectra of the different endmembers which must sum up to one (1) [10]. The LSU is thus used to estimate the fractional abundances of the mixed endmembers by decomposing the subpixel reflectance or emittance from the objects in a scene as detected by the remote sensor and residual errors in the calculation is determined by the RMSE image [10]. The ENVI 5.1 was employed for the abundance estimation using the subsetted ASTER image [11].

The region of interest ROI \textbf{M2} is a prospective area observed to have clay deposits occurring as whitish gray in the field [12], possibly a blind or a fossil hydrothermal system NW of Mawulgo thermal spring as shown in figure 4. Spectral profile of the GPS location shows strong absorption around 2.0-2.4 um signifying clay or other Al-OH group minerals. SAM and LSU was done for \textbf{M2} and the results are shown in Figures 5 and 6.

4. Results and discussion
The ROI \textbf{M2} image was first analyzed using SAM and the result is shown in figure 5 which is depicted in RGB for the 3 endmembers namely Kaolinite, illite and muscovite. An inset of the discriminated endmember pixels at point M2 shows that illite occupies more pixels which are green in colour than kaolinite (Red) and muscovite (Blue). However other regions within the overall image show relatively more pixels as blue signifying possible areas of muscovite and red as Kaolinite pixels.

![Figure 5. SAM Rule image map showing pixels for 3 endmembers with inset at ROI M2](image)

The abundance of muscovite at \textbf{M2} an important clay mineral and indicator of argillic alteration in hydrothermal systems means such a location can serve as a target for further in-depth survey by narrowing targets. The result of the unmixing using LSU is illustrated using a three colour composite of the 3 endmembers in figure 6. The result shows relative abundances of muscovite as red pixels,
Kaolinite as green pixels and illite as blue pixels. The sampled areas at M2 shows predominantly muscovite and illite signifying hydrothermal alteration by the presence of clay minerals but of the Al-OH group. The result also unmixed the pixels that appear to be kaolinite in the SAM analysis and further confirmed areas of illite and muscovite. It is pertinent to note that the presence of illite, a clay mineral, also signifies phyllic alteration of feldspar and is of geothermal significance [9].

The image in figure 7 shows the root mean square error (RMSE) which determines the residual error in the LSU estimation of endmember abundances [13].
The result is evaluated by identifying proportions of bright and dark pixels which respectively indicate high errors and accurately mapped subpixel abundances of targets of interest [13]. The RMSE image mostly identified areas around M2 as well classified by the LSU algorithm and shows the abundance of illite and muscovite while most of the pixels classified as Kaolinite have the highest errors. The LSU was observed to more effectively discriminate altered zones of interest than the SAM technique.

5. Conclusions
The hydrothermal alteration minerals namely kaolinites, Muscovite, illite were detected and mapped in the study, the alterations were observed to be predominantly argillic with Kaolinite group minerals and Al-O-H minerals. The proximity of these alterations to the thermal springs indicates their relation to GT processes. Identified alterations as observed from image spectra greatly conform to the results of XRD of samples collected using GPS field validation which identified minerals including; Kaolinite and Dickite, Hematite and Quartz. This indicates the applicability of the methods for prefeasibility stage GT exploration in unexplored tropical savanna environment. Although ASTER could not discriminate specific minerals but groups, however, the results signifies that alteration zones are identifiable in vegetated savanna especially where they are exposed to a wider area such that the 30m pixel resolution of ASTER SWIR bands could detect it.

In subsequent studies, we intend to use partial sub-pixel unmixing algorithms to discriminate alterations of interest by employing field validated image derived spectra as reference for narrowing targets in unexplored settings.

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