Identification of alteration zones using a Landsat 8 image of densely vegetated areas of the Wayang Windu Geothermal field, West Java, Indonesia

Kristian Edwin Salamba¹, Arie Naftali Hawu Hede², Mohamad Nur Heriawan²

¹ Mining Engineering Study Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung
² Earth Resources Exploration Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung
Jl. Ganesha No.10, Bandung, West Java, 40132, Indonesia.

Email: edwink@gmail.com

Abstract. Remote sensing is a method usually used for conducting geothermal reconnaissance surveys by mapping surface alteration anomalies, which are captured by a satellite sensor. This study analyzes the characteristics of the surface alteration zones in the Wayang Windu geothermal field (WWGF). It employs a remote sensing method using multispectral Landsat 8 imagery and is validated by ground truth data from field surveys. The WWGF is located in Pangalengan, West Java with an elevation of 1500–2600 m.a.s.l., and lies in a quaternary volcanic arc. The rock types in Wayang Windu consist of andesite, basalt, tuff, breccia, and pumice. Fractures and faults are identified as lineaments in this area and based on their structures, were directed to be oriented northwest–southeast and northeast–southwest. This research combined a field survey and remote sensing methods to enhance the spatial data. Field surveys yield 18 spots for obtaining soil samples and laboratory analyses were performed. Spectral reflectance analysis was performed to determine the reflectance and mineral composition of the samples, X-ray diffraction was performed to determine the mineral composition, and X-ray fluorescence was performed to determine the abundance of elements. A scene from Landsat 8 image acquired on September 10, 2013 was evaluated using a principal component analysis-based method. The surface alteration zones in the WWGF correlated with joints and faults. Based on the mineral composition, the surface alteration zones in WWGF were identified as advanced argillic zone with the occurrence of secondary minerals such as cristobalite and halloysite, and a propylitic zone with the occurrence of secondary minerals such as epidote and chlorite.

1. Introduction
Remote sensing is a method used in reconnaissance surveys. This method can map surface alteration anomalies by capturing the spectral reflectance of surface minerals. This method can periodically observe large areas, but it has limitations in tropical conditions, which have high precipitation and dense vegetation [1][2][3][4]. To overcome this problem, this research used principal component analysis (PCA) to enhance mineral spectral reflectance and targets by reducing the impact of atmospheric and vegetation conditions [1][5].
The Wayang Windu geothermal field (WWGF) is located in Pangalengan, West Java, Indonesia (Figure 1) and has a tropical climate with high precipitation and dense vegetation. It is a geothermal system at the transition between a liquid-dominated and a vapor-dominated system. The reservoir consists of the WWGF associated with Mt. Wayang–Windu in the south and Mt. Gambung–Puncak Besar in the north. Geothermal manifestations in this field include fumaroles, steaming and altered ground, and acid-sulfate springs [6].

Figure 1. Morphology of the WWGF based on a Landsat 8 image acquired on September 10, 2013 and Shuttle Radar Topographic Mission 1 arc-second.

2. Data and Methodology

2.1. Data
This research used a Landsat 8 image with an acquisition date of September 10, 2013. The image captured spectral reflectance from path 122 and row 65, sun azimuth 66.27°, sun elevation 60.70°, and scene center time of 03:02:29 GMT. The spatial resolution is 30 m x 30 m. In addition, this research used ground truth from surface soils gathered from 18 points at 9 km x 8 km area to validate the PCA.

2.2. Methodology
Directed PCA (DPCA) is a method that enhances imagery based on the differences between two band ratios [1][5]. The input band ratio images are selected on the basis that one band ratio contains information related to the component of interest (hydrothermal alteration in this case). The second band ratio should contain information about a spectrally interfering component, which is dense vegetation in this case. The DPCA is based on the examination of principal component (PC) eigenvector loadings to decide which of the PC images will concentrate information related directly to the theoretical spectral signatures of specific target materials. The technique is able to predict whether the target material is represented by bright or dark pixels in the PC images according to the magnitude and sign of the eigenvectors. The DPCA was applied to Landsat 8 imagery in the WWGF to identify limonitic and clay materials and also to map the alteration zones by integrating with geographic information system-based image classification.
3. Result and Discussion

3.1. Surface Alteration Zone based on PCA
Landsat 8 imagery has 11 bands acquired by both the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). Bands in Landsat 8 OLI capture 9 bands from visible near-infrared (VNIR) and shortwave infrared (SWIR). The spectral bands used for this study are bands 2–7 to identify surface material (Figure 2).

![Figure 2. Spectral reflectance from minerals and vegetation. Each range of the Landsat 8 band is shown in the column.](image)

The Landsat 8 image was preprocessed using ENVI 5.3 software and the FLAASH algorithm. Preprocessing included the identification of regions of interest, radiometric calibration, and atmospheric correction. The purpose of the preprocessing procedure was to reduce noise in the imagery. After preprocessing, imagery was processed using the DPCA to determine alteration zones in the surface of the WWGF.

The DPCA was used to map clay minerals and limonitic minerals in dense vegetation zones by using two-band ratios [5]. The limonitic zone is represented by band ratio 4/2, and the dense vegetation zone is represented by band ratio 5/4 (Table 1). The clay minerals zone is represented by band ratio 6/7, and the dense vegetation zone is represented by band ratio 5/4 (Table 2).

| Principal Components | Eigenvectors | Eigenvalues (%) |
|----------------------|--------------|-----------------|
|                      | Band ratio 4/2 (band ratio of limonitic minerals) | Band ratio 5/4 (band ratio of vegetation) |
| PC 1                 | 0.01         | -0.99           | 18.77          |
| PC 2                 | -0.99        | -0.01           | 0.08           |
Table 2. Eigenvectors analysis of the two-band ratio of Landsat 8 image for clay minerals. The principal component (in bold) represents clay minerals.

| Principal Components | Eigenvectors | Band ratio 5/4 (band ratio of vegetation) | Band ratio 6/7 (band ratio of kaolinite) | Eigenvalues (%) |
|----------------------|--------------|------------------------------------------|-----------------------------------------|-----------------|
| PC 1                 |              | 0.99                                     | 0.07                                    | 18.87           |
| PC 2                 |              | -0.07                                    | 0.99                                    | 0.02            |

In the WWGF, clay minerals occur as plain ramps (Figure 3). Their occurrence can be related to land use and is mostly found in plantation or paddy fields, which consist of clay materials. Clayey soils can easily hold water and become saturated. Limonitic layered in the WWGF occurs in steep terrain, hillsides, and bare soil.

Figure 3. Clay and limonitic layered distributions in the WWGF.

DPCA can be combined with GIS-based image classification to analyze the distribution of hydrothermal alteration zones and altered hydrothermal minerals and hydrothermal alteration zones in dense vegetation area [1]. The combined technique uses a two-band ratio between the altered mineral band and the vegetation band. The ratio band used for DPCA of each altered mineral shown in Table 3.
### Table 3. Band ratio for DPCA in Landsat 8 image.

| Altered Mineral | Vegetation band ratio | Mineral band ratio |
|-----------------|-----------------------|--------------------|
| Quartz          | band 3 / band 4       | band 7 / band 2    |
| Alunite         | band 5 / band 2       | band 6 / band 7    |
| Kaolinite       | band 5 / band 4       | band 6 / band 7    |
| Chlorite        | band 5 / band 3       | band 6 / band 2    |
| Epidote         | band 3 / band 4       | band 6 / band 2    |

In this research, the selection of altered minerals is identified based on the mineral assembly of the hydrothermal alteration zone. The ratio band that is used in this research is based on the USGS Spectral Library and contrasts spectral reflectance between mineral and vegetation. Geological setting based on geological of the Garut and Pameungpeuk quadrangle, Java [7]. The advanced argillic assembly is represented by secondary minerals: quartz, alunite, and kaolinite; the propylitic assembly is represented by secondary minerals: chlorite and epidote. Advanced argillic and propylitic assemblies were chosen based on previous research [8].

Epidote and chlorite were mostly distributed in Malabar-Tilu volcanic (Qmt) formations (Figure 4a) which consist of tuff and laharc breccia containing minor amounts of pumice and lavas. Other rock formations such as young volcanic (Qyw), undifferentiated efflata deposits of old volcanic (Qopu), Waringin-Bedil andesite, and old Malabar (Qwb) formations, feature lower distributions of epidote and chlorite.

Kaolinite and alunite are mostly distributed in formations of Qopu (Figure 4b). The Qopu formations consist of fine to coarse dacitic crystalline tuff and tuffaceous breccia containing pumices and old andesitic-basaltic laharc deposits. Other rock formations, such as Qyw, Qmt, Waringin-Bedil andesite, and Qwb formations, feature lower distributions of kaolinite and alunite. Quartz is mostly distributed in Qmt formations (Figure 4c). The distribution of quartz is predominantly in hillsides or steep terrain near Mt. Gambung, Mt. Wayang, and Mt. Windu. Quartz can occur as a secondary mineral due to hydrothermal alteration and as a primary product of volcanic activity.

A fuzzy logic algorithm is the last process used in DPCA to combine several raster images into a single raster based on dominant similarities between them. In this research, the fuzzy logic algorithm was used to determine the advanced argillic alteration zone and the propylitic alteration zone. The advanced argillic alteration zone consists of alunite, quartz, and kaolinite; the propylitic alteration zone consists of chlorite and epidote.

Advanced argillic and propylitic zones occur on the surface of the WWGF (Figure 4d). Some areas cannot be mapped because there is no similarity between the spectral reflectance on the surface of both alteration zones and because of very dense vegetation on the surface preventing remote sensing identification.

### 3.2. Lineaments Identification from Landsat 8 Image

The lineament pattern identified from Landsat 8 image interpretation is the same as the regional geology structure (Figure 5a). The lineament pattern in this area is related to regional faults with directions southwest–northeast and northwest–southeast.

The lineament distribution in the WWGF was translated into lineament density (Figure 5b). The purpose of lineament density is to identify areas that have high-density lineament. High density lineament potentially become evidence of permeable zones and media for hydrothermal fluid flowing from a reservoir to the surface [9].
The most areas of the WWGF have moderate to high lineament density (4–7 km/km2), but near the mountain, this increases to 8 km/km2 (shown in the red area), meaning that lineament density increases near the mountain (see Figure 5b). This lineament density is related to a hydrothermal alteration assembly—mostly secondary minerals on the surface that show up near areas with high lineament density.

Figure 4. Distribution of minerals in the WWGF: (a) chlorite and epidote distribution; (b) kaolinite and alunite distribution; and (c) quartz distribution. (d) Advanced argillic and propylitic zones in the WWGF.
3.3. Identification of soil samples from the surface of the WWGF

The identification of soil samples from the surface were used to validate the data from Landsat 8 imagery processing. In this research, 18 soil sample spots were used to validate the data (Figure 6). Manifestations of geothermal activity in the WWGF were also used to validate the Landsat 8 imagery processing. Identification of soil samples was done using X-ray diffraction (XRD) analysis, spectral reflectance analysis, and X-ray fluorescence (XRF) analysis to determine the mineral composition of the sample.

The identification of soil samples was mostly in agreement with the Landsat 8 imagery processing. However, some were misinterpreted; from Landsat 8 imagery processing, K-9 and K-13 were identified as propylitic alteration zone, but from XRD analysis and spectral reflectance analysis, K-9 and K-13 have secondary minerals of halloysite, cristobalite, and quartz. This means that according to the XRD analysis and spectral reflectance analysis, K-9 and K-13 should be advanced argillic alteration zones. This problem can be explained as follows:

1. The surface features very diverse. Soil samples were collected from a 0–1meter depth from ground level. The soil sample was blended for XRD, XRF, and spectral reflectance analysis, but the Landsat 8 image only captured the surface.
2. The spatial resolution of Landsat 8 is 30 x 30 meters, and diverse mineralization in one pixel of the Landsat 8 image is difficult to see.

The secondary minerals from each spot of the soil samples was an alunite-kaolinite assembly and a chlorite assembly. This means that the alteration zone in the WWGF is an advanced argillic and propylitic zone, as identified in previous research [8]. This alteration assembly indicated that the pH of the formation was acidic to neutral.

Figure 5. Lineament in the WWGF: (a) overlay with alteration zone; (b) in lineament density form and overlay with WWGF’s morphology.
Figure 6. Location of soil samples and hydrothermal manifestation in the WWGF.

Based on XRD analysis, minerals on the surface of the WWGF consist of clay and non-clay minerals. The non-clay minerals associated with clay minerals on the surface are as follows:

1. Iron oxide (hematite [Fe₂O₃]) and iron hydroxide (goethite [Fe₂O₃.H₂O])
2. Aluminum hydroxide (gibbsite [Al(OH)₃])
3. Silicon oxide (quartz [SiO₂] and cristobalite [SiO₂])
4. Zeolite
5. Sulfate (alunite [KAl₃(SO₄)₂(OH)₆])
6. Feldspar

The results of XRD and spectral analyses were validated using XRF analysis which provided data about the abundance of elements in the sample, and this data can validate the occurrence of minerals in the soil sample. The elements that were used to validate the X-ray analysis and spectral reflectance analysis were as follows:

1. Silicon (Si)
2. Iron (Fe)
3. Aluminum (Al)
4. Sulfur (S)
Aluminum is a key element of clay minerals, which occur across the surface of the WWGF (Figure 7a). The mass percentage of Al₂O₃ in the WWGF ranged from 30–45%. This is because of the hydrolysis process of aluminum silicate minerals such as feldspar, pyroxene, amphibole, and mica. In this process, they repeatedly react with water, releasing aluminum ions that move and settle in the surface of the soil. This is related to the occurrence of clay minerals in the WWGF.

Iron occurrence is related to the distribution of limonitic minerals in the WWGF (Figure 7b). The area with the highest mass percentage of Fe is likely to be the most weathered area in the northern region of the WWGF. This correlates with the limonitic mineral distribution in the northern region of the WWGF observed during Landsat 8 image processing.

The area with the highest percentage of Si is likely to be near an intrusion or fault zone with high permeability; thus, many silicate minerals, including quartz, cristobalite, and opal, will occur there (Figure 7c). This is related to the occurrence of Si, which mostly occurs near Mt. Wayang and Mt. Windu, both of which feature the intrusion of andesitic rocks.

Sulfur is a constituent element of alunite, which requires a high temperature (around 200°C) and acidic pH to form (Figure 7d). Alunite occurs with acidic gases such as CO₂ and H₂S because of the boiling and evaporation of deep fluids and condensation in rocks near the surface. The distribution of high sulfur content is related to K-18, K-8, K-30 and K-19, and these sample points which were identified to be advanced argillic alteration zones. It is correlated with Landsat 8 imagery processing and surface manifestations of geothermal activity; there is a fumarole in the Wayang crater near K-18, and the Kertamanah hot spring is near K-8. These findings agree with previous research [10].
3.4. Control Factor of Alteration in the WWGF

Triggers for alteration processes in the surface of the WWGF are probably faults, which occur as lineaments in the surface of the WWGF. Fumaroles and hot springs are evidence of the occurrence of faults in the subsurface of the WWGF. The correlation between lineament density and the occurrence of a hydrothermal alteration zone in the surface of the WWGF is also evidence of faults as the main factor in the hydrothermal alteration zone.

4. Conclusions

The hydrothermal alterations at the surface of the WWGF are advanced argillic and propylitic zones. The former contains the secondary minerals alunite, cristobalite, and quartz, and the latter contains the secondary minerals chlorite and epidote. The controlling factor of hydrothermal alteration in the surface is probably the geological structure of WWGF, which allows hydrothermal fluid to alter the rocks near the surface. Remote sensing with DPCA method integrated with GIS-based analysis successfully enhanced the hydrothermal alteration zones. The alteration zones extracted by this combination were confirmed to be plausible and consistent with the ground truth data. However, there are some considerations related to unsuccessful of DPCA to enhance the alteration zones that may be caused by the limitation of spatial resolution of Landsat 8 image and vegetation cover conditions.

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