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Use of Space-borne imageries in Mapping of Hydrothermal Alteration Zones and Geological Structures in the Eburru Geothermal Complex, Kenya

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Space-borne imagery, hydrothermal alteration, Geological structures, Eburru

ABSTRACT

The study used space-borne images acquired from the Landsat-8/Operational Land Imager (OLI) to map alteration zones and structures within the Eburru Geothermal Complex, Kenya. The Eburru Geothermal Complex lies in the Eastern African Rift System which is part of the Afro Arabian rift system that extends from the Red Sea to Mozambique. Its lithologic units consists of pyroclasts, trachytes, pantellerites, basalts and associated lavas. The images were pre-georeferenced to a UTM zone 37 South projection using the WGS-84 datum. The purpose was to increase precision of geothermal well siting by identifying surface anomalies resulting from hydrothermal alteration. The Landsat image (Path/Row 121/59) was obtained from the U.S. Geological Survey's Earth Resources Observation System (EROS) Data Center (EDC). They were acquired on 26th July 2018 during dry season with only 5% cloud cover. Gram-Schmidt pan sharpening method was used to increase the spatial resolution. Principal Component analysis was used to map altered hydroxyl and ferric oxide zones around fumaroles. Band ratio technique was applied and filtered according to the statistically calculated ratio intervals for these hydrothermal minerals. Target detection method for reference spectral analysis using ENVI 5.0 detected representative hydrothermal altered deposits and iron oxides which are minerals associated with fumaroles. This technique was found to be efficient for mapping of hydrothermally altered deposits such as iron oxide minerals, argillaceous zones and fumaroles. Filtering of vegetation was done using NDVI technique.

1. Introduction

The use of space borne images in mapping of geological features and hydrothermal alteration zones has increased over the years due to fruitfulness provided by the resulting image analysis (Yetkin, 2003). Improvements in the wavelength coverage, spectral resolution and quality of remote sensing imagery have led to the extensive application of these data sets in exploration and site characterization (Wendy and Coolbaugh, 2005).

Hydrothermal alteration is the change in mineralogy as a result of interaction of the rock with hot water fluids. The hydrothermal fluid processes alter the mineralogy and chemistry of the host rocks that can produce distinctive mineral assemblages which according to the location, degree and duration of those alteration process (Mia and Fujimitsu, 2012). These hydrothermal products are mapped as zoned patterns on the surface. The importance of such alteration patterns makes remote sensing one of the standard mapping procedures in geology due to its high efficiency and low cost (Mia and Fujimitsu, 2012; Yetkin, 2003). Areas characterized by high hydrothermal alteration intensity are useful indicators of identification of geothermal resources. The notable surface hydrothermal features include: fumaroles, hot springs, altered grounds (highly oxidized zones) among others. As a result, they are easily detected by the sensors. The images acquired are analyzed and interpreted to delineate zones of exposure and extreme weathering.

The data is thereafter used by geoscientists (geologists, geophysicists, and geochemists) to site and target productive geothermal wells. There are many studies around the world related to hydrothermal alteration mapping using multi-spectral satellite images especially Landsat and ASTER (Mia and Fujimitsu, 2012). The major types of alteration found in volcanic areas are pottasic, phylic, propylitic and silicification. Each type of alteration has diagnostic minerals in their respective rocks (Mia and Fujimitsu, 2012). Satellite imaging plays an important role in differentiating the representative minerals for different types of alteration. Alteration zones are correlated with geological structures that control the reservoir permeability. Therefore locating surface hydrothermal alteration zones helps to determine the presence of upflows from geothermal reservoirs (Mia and Fujimitsu, 2012).

This research intends to use acquired images for the mapping of hydrothermal alteration products in Eburru geothermal field which could demonstrate the use of the method as an exploration tool in a geothermal exploration project.

1.1.Location of the study area

The study area is located in the Nakuru County, about 150 km northeast of Nairobi, Kenya. It is bounded by latitudes 36 ° 00’ 00.0” and 36 ° 40’ 00.0” S; and longitudes 0 ° 70’ 00.0” and 00 ° 90’ 00.0” E; covering an area of approximately 120 km ^{2}. It bounds Lake Naivasha to the North and Lake Elemetaita to the South.

1.2. Hydrothermal alteration

The processes acting within a volcanic hydrothermal system including fluid-rock interaction, boiling and mixing are considered the primary cause of various surface waters and steam vents as well as the observed secondary mineralogy (Bjorke, 2010) . The common minerals that can be observed by space-borne images include: alunite, kaolinite, opal, calcite, muscovite, montmorillonite, chlorites, gypsum and tincalconite. Space borne imagery mapping of hydrothermal minerals is done by assigning mineralogy on their spectral signatures eye

(Lillesand, Kiefer, and Chipman, 2015). Their broad absorption features and spectra are absorbed by the space-borne sensors. The resulting images are interpreted and consequent recommendations done. Surface hydrothermal alteration zones are useful components of a suitable geothermal site. In order to identify these zones, it is necessary to map the principle alteration assemblages and associates found in aluminosilicate rocks within the region of interest. Hydrothermally altered rocks are characterized by unusually colorful rocks (Yetkin, 2003). Certain minerals are associated with hydrothermal process such as iron-bearing minerals (goethite, hematite, jarosite, limonite); hydroxyl bearing minerals such as kaolinite and K micas (Mia and Fujimitsu, 2012). They show diagnostic spectral features that allow their remote identification (Hunt, 1980). The major iron oxide species are formed from weathering of sulfides and absorb energy at different frequencies in the VNIR/SWIR (Rowan, 1983), (Mia and Fujimitsu, 2012), providing a means of discrimination using multispectral scanners.

1.3. Structural Geology of Eburru area

Faults are the prominent structures controlling geothermal surface activities in Eburru-Badlands-Elementaita prospect (KenGen, 2018). Faults control geothermal surface activities in the study area. The structures were formed during different periods with the oldest being the NW-SE faults formed during the formation of the rift (2-7Ma). Some faults have a NE-SW and ENE-WSW orientation dipping to the northwest direction. The Eastern Eburru pantellerites are the youngest rocks and are dated about 400 years ago (Clarke et al. 1990). The area is also characterized by open fractures running many kilometers and with a few meters opening. These fractures are considered important permeability features (KenGen, 2018).

1.4.Problem statement

The traditional mapping of geological elements and hydrothermal alteration are hindered by terrain ruggedness and accessibility. Other challenges such as trespassing restrictions and logistical issues decelerate mapping activities in an area of interest. These challenges usually result in delays that indirectly increase the cost of project implementation. In the process, data acquisition and database update is hindered. Space-borne image platforms are emerging techniques for mapping geology, detecting surface temperature anomalies and identifying prospects including hydrothermally altered minerals.

There is need to incorporate remote sensing in the mapping activities to solve some of the highlighted challenges.

1.5. Study objectives

The study objectives are as follows:

1. To map hydrothermal altered minerals in the Eburru geothermal complex using satellite image analysis methods such as color composite, band ratio, component principal analysis and spectral library analysis.
2. To develop a target alteration map based on interpretation of the space-borne image features.

2. Literature review

The use of remote sensing to map alteration is not a new idea. Its use can be traced back to the 1960s when the first satellite was launched. Use of digital processing and analysis began in the 1960s with early studies of airborne multispectral scanner data and digital aerial photographs. This section provides theoretical and empirical information from publications on topics related to the research problem. Illite (a low-temperature clay) occurs as a mixed smectite-illite interstratified mineral exhibiting a property between two clays minerals. Several studies have been advanced along this line as discussed below.

Onywere et al. (2012) used multispectral Landsat satellite imagery of 1986 Thematic Mapper (TM), 2000 Enhanced Thematic Mapper (ETM) and SPOT imagery 10 m (resolution) of 2007 to investigate anthropogenic activities within Lake Naivasha and its surrounding. The study partially covered the North Eastern parts of Eburru Forest, Lake Elementaita and Gilgil area, Nakuru County Kenya. This study analysed spectral reflectance contrast of the vegetation cover within the area.

Pour et al. (2013) carried a geological analysis coupled with Remote Sensing in the detection of hydrothermally altered rocks and associated structural elements associated with gold mineralization in Bau Gold Mining District, Malaysia. The approach used Enhanced Thematic Mapper plus (ETM^+) hyperion and Phased Array Type L-band Synthetic Aperture Radar (PALSAR) to delineate gold mineralization in the area. They concluded that analysis of spectral signatures of minerals associated with gold deposition such as clays, iron oxides and orientation of structural elements coupled by image interpretation of DPC images is essential in determination of suitable areas for gold exploitation.

Brandmeier et al. (2013) used Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images to characterize alteration by using hyperspectral field spectrometry data and geochemical analysis in Southern Peru. The research located possible caldera based on alteration patterns of rocks within the study area.

Further studies by Van der Meer et al., (2014) combined the aspects of surface deformation, gaseous emission, mineral mapping, heat flux measurements and geobotany to study the use of geologic remote sensing for geothermal exploration in the La Pacana Caldera (Chilli) area. This study concluded that geologic remote sensing in geothermal systems is not mature and there is need to integrate it in a geothermal framework. Classification of ASTER imageries for various hydrothermal minerals such as illite, alunite, gypsum, silica content and lake precipitates was carried out during the study.

A study by Munyiri (2016) comprehensively used high resolution DEM images in the analysis of structures within the Olkaria geothermal complex. The study integrated structural geology, soil gas sampling and remote sensing to delineate geothermal features. It is evident that application of space-borne image analysis in detecting hydrothermal alteration zones and geological evidence is a method that warrants scrutiny and discussion.

Braddock et al. (2017) used satellite observations of volcanic activities in the monitoring of geothermal and volcanic hazards at Aluto Volcano, in Ethiopia. Their study investigated the temporal changes in fumarole temperatures and spatial extent of Aluto, a restless volcano in the Main Ethiopian Rift (MER), in order to better understand the controls on fluid circulation and the interaction between the magmatic and hydrothermal systems. Pixel-integrated temperature variation of the Thermal infrared (TIR) satellite images, acquired by the ASTER over the period of 2004 to 2016, were used to generate time series of the fumarole temperatures and areas. Although the study did not focus on hydrothermal alteration, it comprehensively discussed fault controls associated with hydrothermal alteration along these zones.

Eldosouky et al. (2017) used remote sensing and aeromagnetical data to detect hydrothermal alteration areas in Wadi Allaqi area, South Eastern Egypt. They applied band ratios and crosta technique of principal Analysis (PCA) using LandSat-8 to highlight hydrothermal zones and structural elements such as faults in the area. Center of Targeting (CET) grid analysis and CET porphyry analytical technique was used to construct structural complexity heat map and probable mine zones. The analysis of fault density visa vis hydrothermal alteration zones matched the known mineralization zones in the area.

2.1.Limitations of the study

The study has several limitations. First, the spectral libraries have no chemical or physical information available. Consequently, the technique cannot authoritatively distinguish various characteristics such as crystallography of specific minerals. Secondly, the measurement of spectral response of hydrothermal surfaces in vegetated areas is more difficult because the rock surface is obscured.

3. Materials and method used

3.1. Data

A cloud-free level 1T (terrain corrected) Landsat-8/ OLI imagery was obtained from U.S Geological Survey Earth Resources Observation and Science Center. These images were downloaded from the USGS website. Spatial resolution is about 30m. The image was corrected for geometric distortions and projected to geographic (lat./long.) coordinate system and WGS-84 datum. Internal Average Relative Reflectance (IARR) method was used to do atmospheric correction. ENVI 5.0 and ESRI ArcGIS 10.3.1 programs were used for preprocessing and image analysis.

3.2. Methods

The hydrothermal mapping methods used for the study are as follow:

- ✓ Color Composite
- ✓ Band Ratio
- ✓ Principal Component Analysis
- ✓ Structural mapping

4. Results and Discussion

4.1.1. Color composites

In displaying a colour composite image, three primary colours (red, green and blue) are used. The idea behind color composite technique is to combine the multispectral information with the visible wavelength region, in order to make it visible to the human eye (Lillesand et al. 2015). This enhancement is achieved by combining bands in the visible and in the infrared portions (Mia and Fujimitsu, 2012). A true color image was produced with Landsat 8 visible bands 4, 3 and 2 (Red, Green and Blue) (Figure 1a). With the band combination, rock exposures appeared as brown, vegetated areas as green and built up areas as white. This band combination is applicable for exploratory analysis (Frutuoso, 2015). Alteration zones are identified as (brown), vegetated areas as green, rivers and lakes as blue. False color was created using bands 5, 6 and 7 (R, G, B) (Figure 1b). Vegetated areas appear in orange, rock exposures (blue), water (black) while some hydrothermal alteration features appear as blue.

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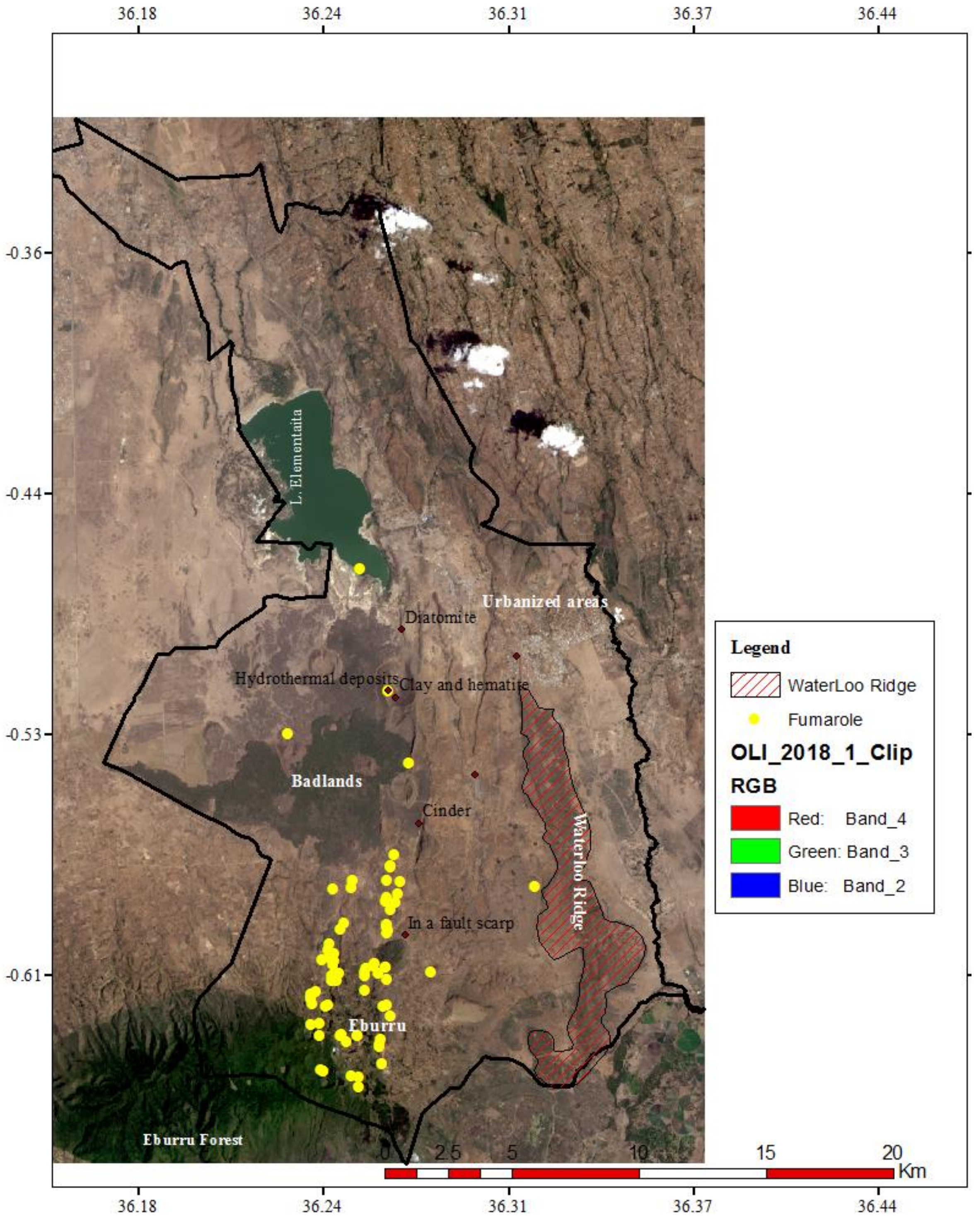

Figure 1a. Composite map RGB 4:3:2

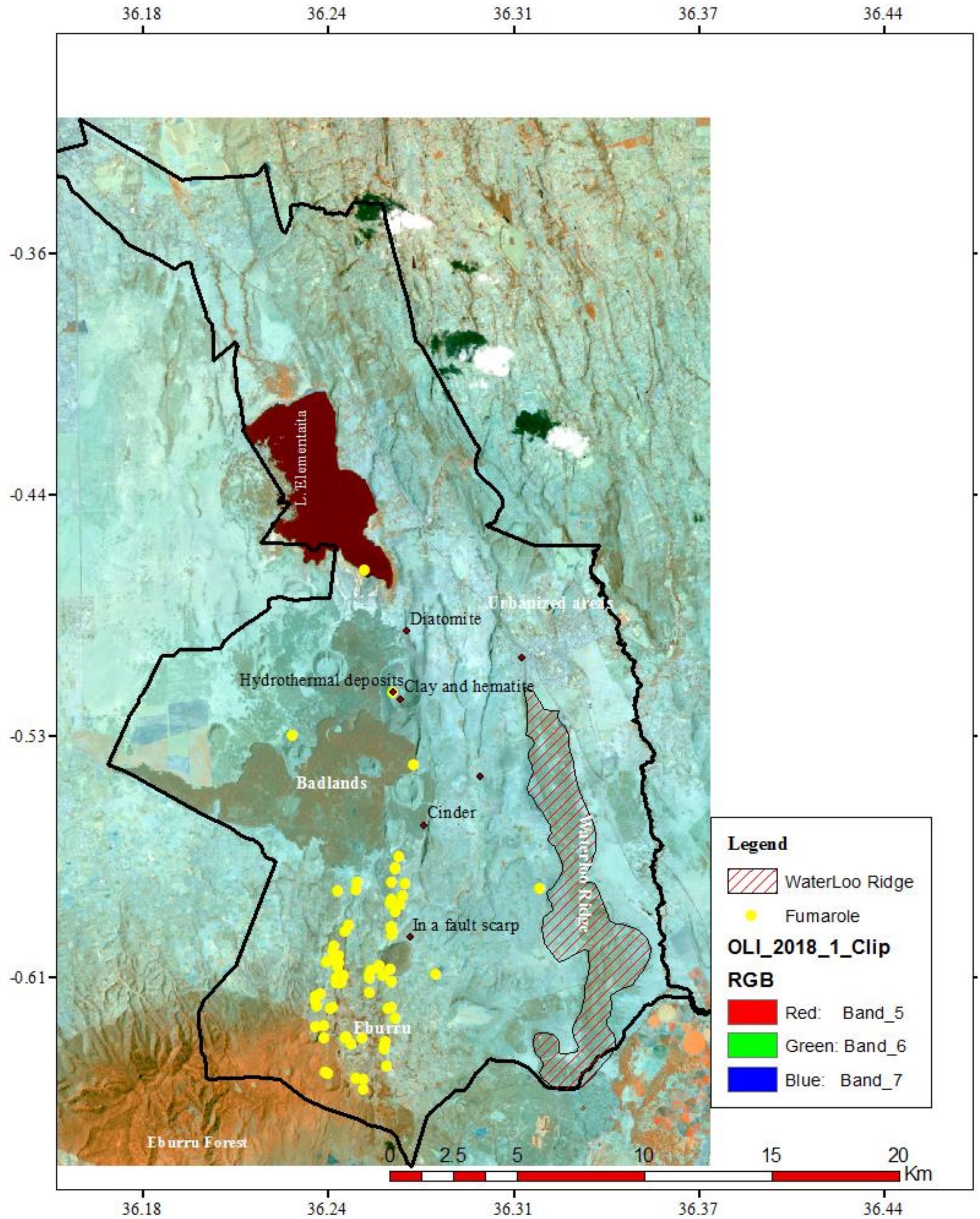

Figure 1b: Composite map of RGB (5:6:7)

4.1.2. Band Ratio

Band rationing is a multispectral image processing method that includes the division of one spectral band by another. They are enhancements resulting from division of Digital Number values in one spectral band by corresponding values in another band (Lillesand, Kiefer and Chipman, 2015). They convey the spectral or color characteristics of image features regardless of variations in the scene illumination conditions. Band ratio images are known for enhancement of spectral contrasts among the bands considered in the ratio operations and have successfully been used in mapping alteration zones (Mia and Fujimitsu, 2012). Band ratio Band rationing is expressed mathematically as follows:

DN new = DN a / DN b………………………………………………………………..…………… **(1)**

For a pixel, if band a = 50 and band b = 25, then the band ratio DN new = 2 (2.0)

Landsat 8 OLI band ratios of 4/2 (greyscale) are used to highlight areas with abundant iron (Frutuoso, 2015). They appear as bright tones/pixels (Figure 2). The light colored tones also reveal zones of clay alteration minerals such as illite, montmorillonite and alunite (Frutuoso, 2015).

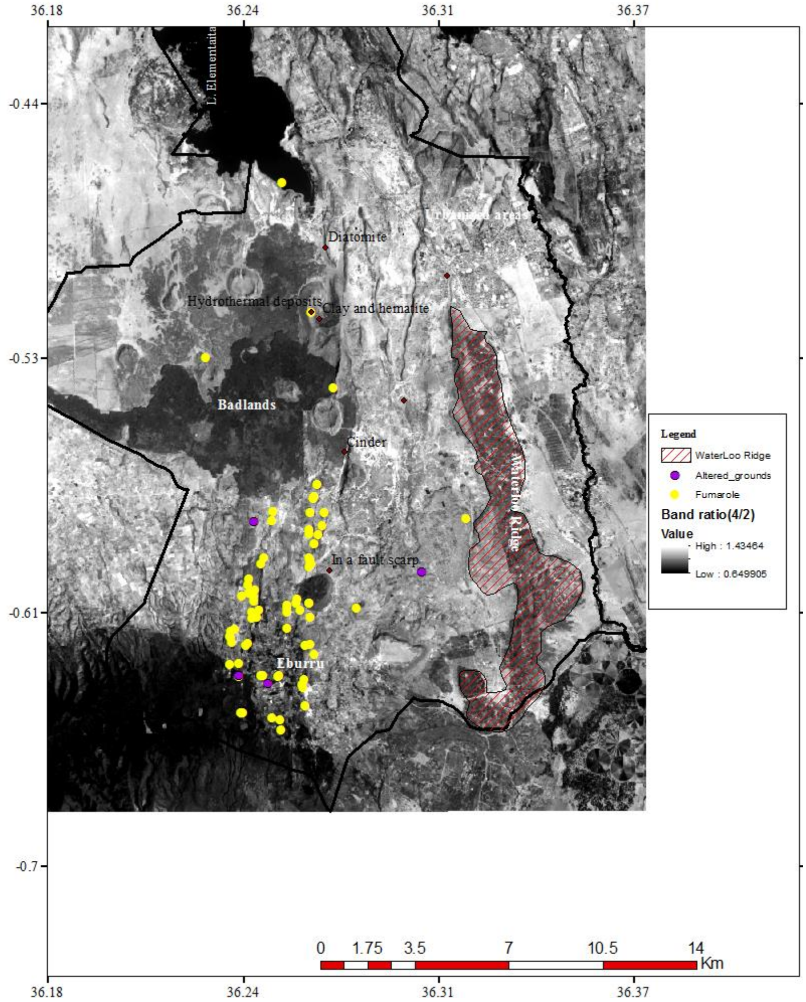

Figure 2: Band ratio 4/2 analyzed altered mineral deposits

Band rationing has technique is usually limited by vegetation density (Frutuoso, 2015). Consequently, Principal Component Analysis is applied to minimize such effects.

4.1.3. Principal component analysis

The principal components analysis (PCA) uses the principal components transformation technique for reducing dimensionality of correlated multispectral data (Lillesand et al. 2015). The analysis is based on multivariate statistical technique that selects uncorrelated linear combination (eigenvector loadings) of variables in such a way that each successively extracted linear combination, or principal component (PC), has a smaller variance (Singh and Harrison, 1985; Mia and Fujimitsu, 2012). The principal component image results from linear combination of the original data and eigenvectors on a pixel-by-pixel basis throughout the image (Lillesand et al. 2015). Six Landsat 8 bands (2, 3, 4, 5, 6 and 7) were applied for the study. The output eigenvector matrix values are represented in Table 1. PC1 (Principal Component 1) is composed of positive values for all 4 bands and is responsible for all scenes of brightness. It has a variance data of 99.1 %. PC2 has a 0.6% variance representing vegetation cover (appear as bright pixels in RGB). The first three PCs combined in RGB composite contain most of data variance. These PCs are useful for mapping of lithology and hydroxyl bearing minerals (Frutuoso, 2015). Landsat 8 bands 2, 5, 6 and 7 are useful in mapping of hydroxyl bearing minerals. In Figure (3), areas with high concentration of Hydroxyl and iron oxides appears light toned, while vegetated areas are dark pixel colored.

Table 1: Eigen values for Principal component Analysis of Landsat 8 bands 1, 2, 3, 4

	PC1	PC2	PC3	PC4
Band 1	0.30337	0.47089	-0.30951	-0.49556
Band 2	0.30488	0.38094	-0.30358	0.80026
Band 3	0.33289	0.06807	-0.50137	-0.24252
Band 4	0.42993	0.42864	0.74700	-0.03508
Percent of EigenValues	99.1655	0.6344	0.2031	0.0303
Accumulative of EigenValues	99.1655	99.7999	100.0030	100.0333

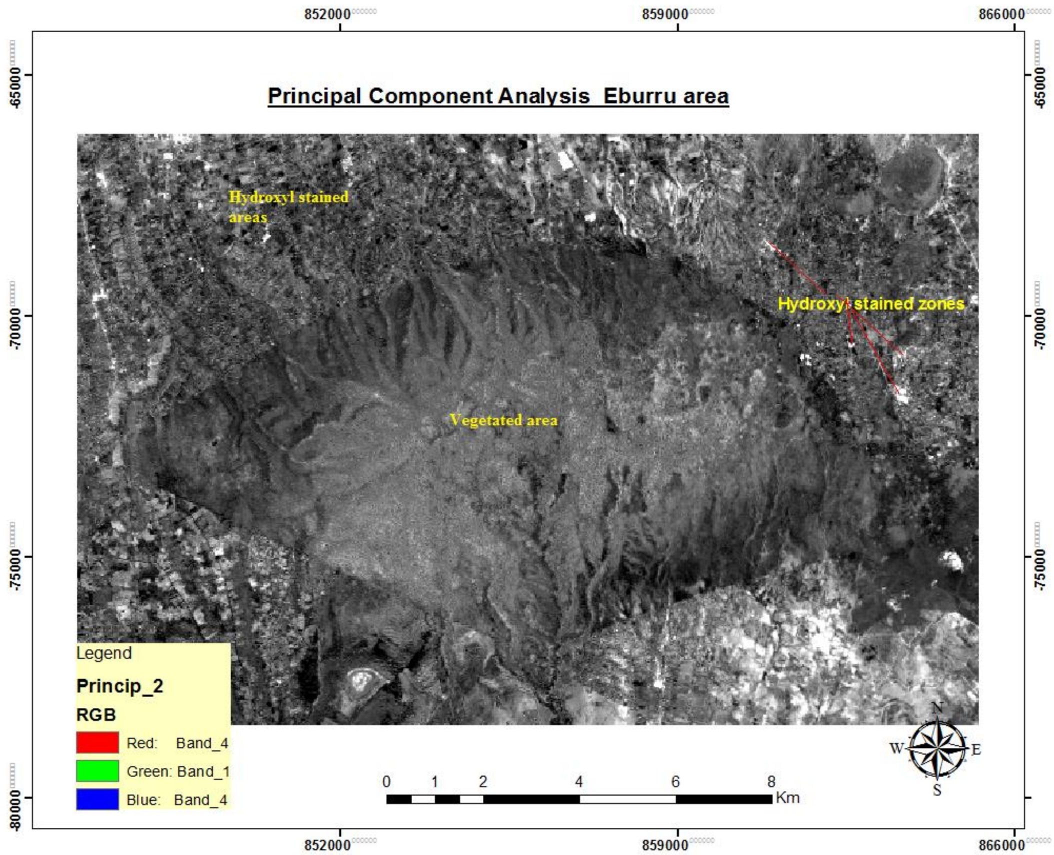

Figure 3: PCA map of Eburru

4.2.Structural mapping

This was done by extracting and development of geological and geomorphological features of the Digital Elevation Model map of the study area. The structural information extracted consists of NE-SW, N-S and NW-SE orientation along major regional faults (Figure 4). The structures are important in controlling geothermal fluid movement.

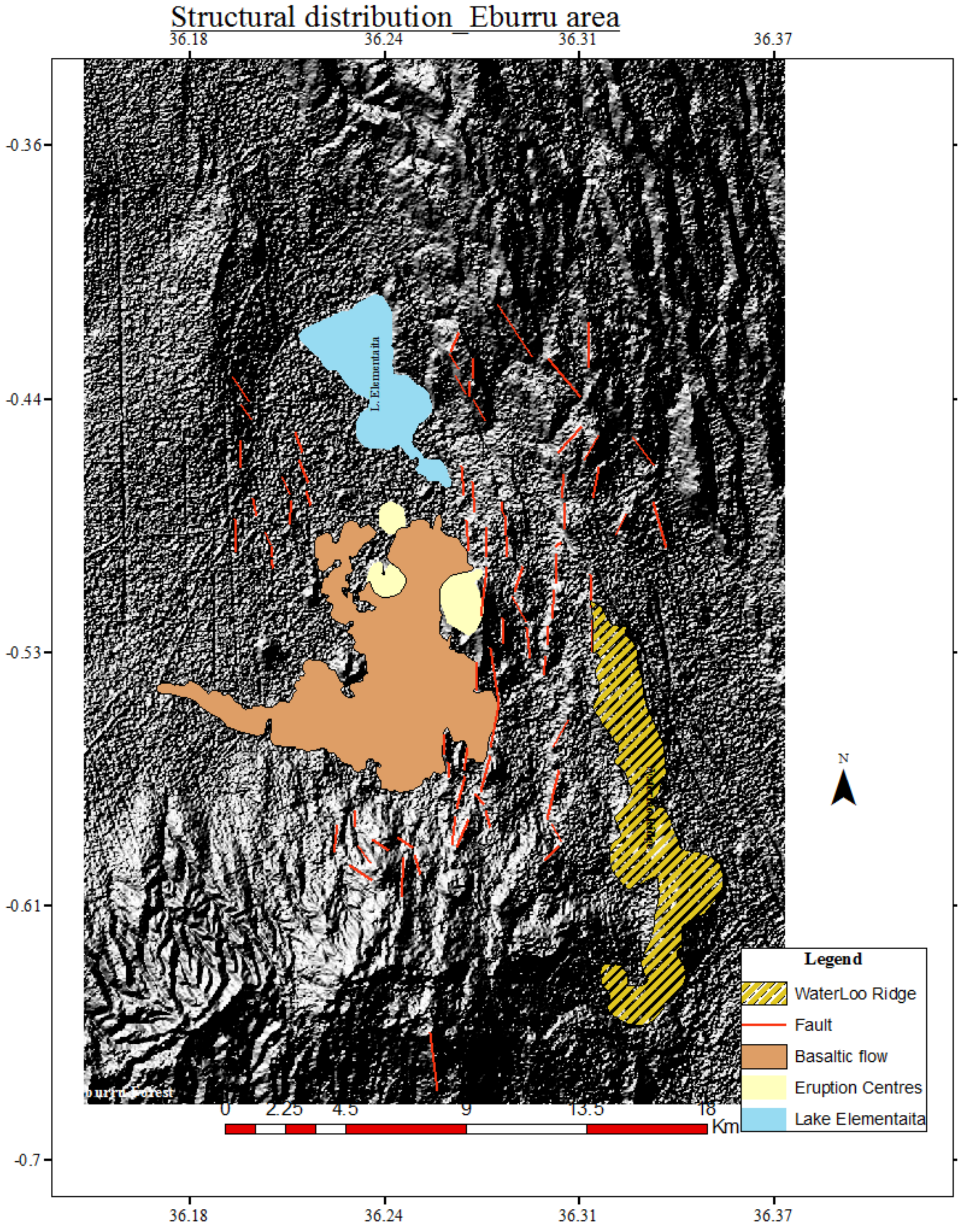

Figure 4: Structural patterns of Eburru area

4.3. Target alteration map

A temperature distribution map was generated by spatially interpolating the surface geothermal manifestation features to their respective measured surface temperature (Figure 6). The temperature data was obtained from soil temperature measurements and heat loss surveys measurements done by KenGen (2018). The Inverse Distance Weighted (IDW) spatial interpolation technique was used to generate the target Iso map. The surface hydrothermal features (fumaroles, altered ground, and eruption centers) were overlaid over the natural color RGB composite map of the Eburru Badlands area.

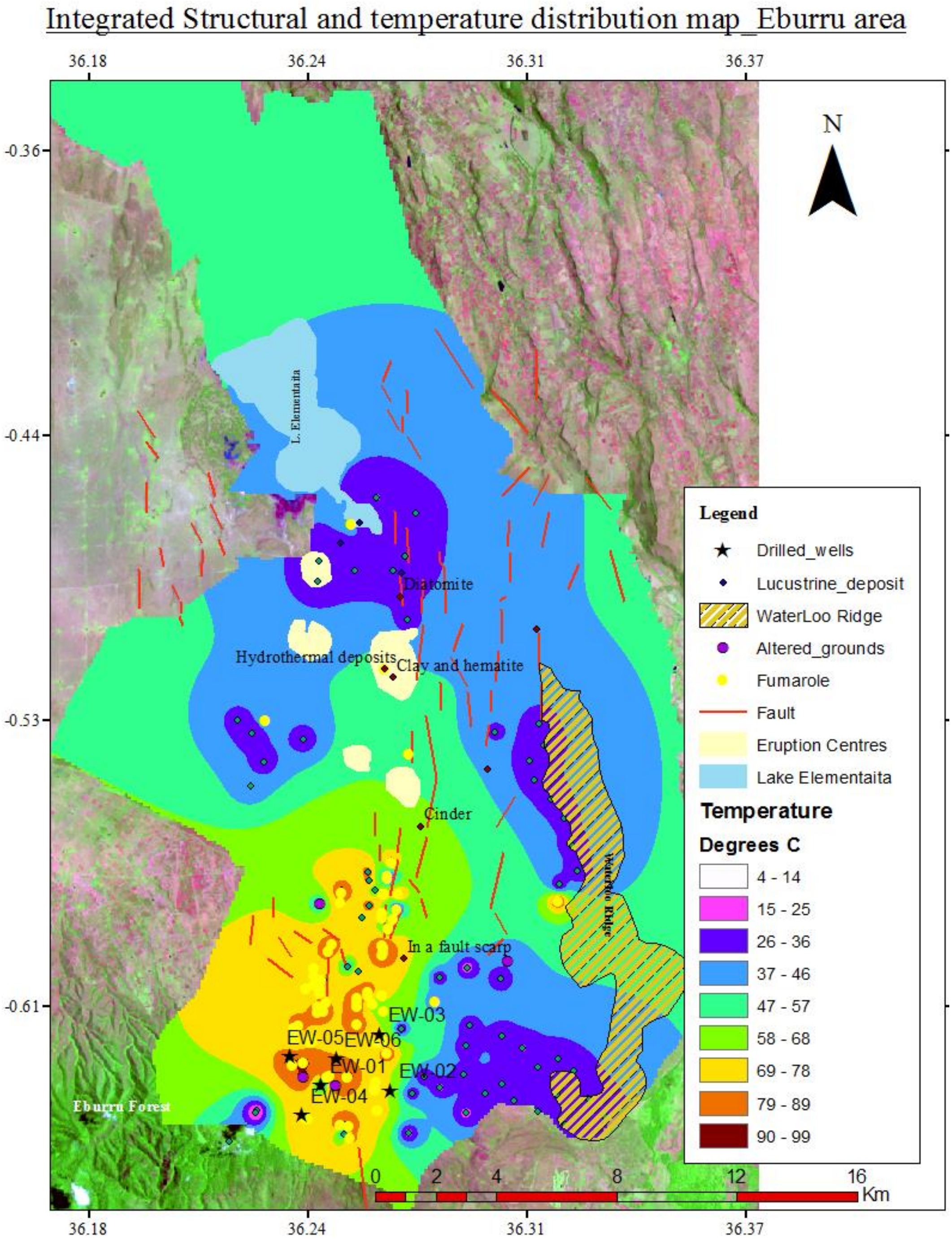

Figure 5: Hydrothermal alteration target map of study area

It is evident from the temperature distribution map that areas around the Eburru massif caldera are flanked by numerous surface geothermal manifestation features. Fumarole temperatures are highest in Eburru massif area and lowest to the NE. SE parts of the study area around the Eburru forest depict low temperature distribution (15-36^0 C). KenGen's drilled deep wells i.e. EW-01, EW-02, EW-03, EW-05 and EW-06 are located in areas characterized by moderate to high surface temperature distribution. Well EW-01 encountered up flowing fluids and has been able to sustain discharge. This is an indication of recessive geothermal activities (KenGen, 2018). The SE area around the waterloo Ridge is characterized by low concentration of surface geothermal manifestation features. According to KenGen (2018), these zones depict existence of low temperature minerals such as zeolites, silica and chalcedony. Their presence indicates low grade alteration temperatures <150 °C.

The Northern parts of the study area (Badlands) is characterized by sparse population of surface hydrothermal features. It is however fault dominated. These faults are oriented in N-S, NE-SW and E-W direction (Figure 5). Calcite and Silica deposits are also found in the basaltic lava flows that flanks the area. The Northern areas around Lake Elementaita are flanked by lacustrine sediments. Surface hydrothermal manifestation features such are less abundant in these areas.

5.0. Conclusion and Recommendation

The space-borne image analysis techniques such as color composite, band rationing and Principal Component Analysis was applied to establish geothermal alteration zones within the Eburru-Badland area. A layer stacked true color composite multispectral image with natural band combination of 4, 3, 2 (RGB) was used for preliminary identification of outcrops, water bodies and vegetation. Vegetation appeared as light green, rock outcrops (brown) and water as dark green. To obtain further clarity of these features, False color composite band combination images of 5, 6, 7 (RGB) were analyzed. Alteration zones appeared as (brown), vegetated areas as green and water bodies as black.

Band ratio (4/2) of Landsat 8 OLI in greyscale was applied to highlight areas with anomalous concentration of ferrous minerals. These areas appeared in bright pixels. Principal Component Analysis demonstrated iron oxides and hydroxyls in the area of study. High concentration of hydroxyl minerals were observed around alteration zones and fumaroles in the Eburru area. The altered showed light toned pixels, while vegetated areas appeared dark colored. Structural delineation was carried out on a Digital Elevation Model image of the study area. The extracted faults were noted to show NE-SW, N-S and NW-SE orientation. Most geothermal manifestation features trended along the structural features. Combined map of eruption centers, surface alteration features relationship between hydrothermal features and geological structures. The temperature distribution map was created by overlaying measured surface temperature data over the composite images and interpolating them using the Inverse Distance Weighted (IDW) method. High temperature variation was observed in areas with abundant geothermal manifestation features such as Eburru Massif area. The areas North of Eburru showed declining temperature.

It can therefore be concluded that analysis of space borne imageries is an efficient method useful in delineation of hydrothermally altered minerals. However, this study should include the systematic rock sampling to reveal the lithology, geochemistry of the area, to clarify the accuracy of the alteration maps. Ultimately, I propose the use of high spatial and spectral resolution images in the study to enhance the research findings.

REFERENCES

Achieng, J., Mutua, J., Mibei, G., Olaka, L., & Waswa, A. K. "Mapping of Hydrothermal Minerals Related to Geothermal Activities Using Remote Sensing and GIS: Case Study of Paka Volcano in Kenyan Rift Valley". *International Journal of Geosciences*, *08*(05), (2017), 711–725. https://doi.org/10.4236/ijg.2017.85039

Bjorke, J. K. "Fluid-rhyolite interaction in geothermal systems, Torfajokull Iceland-secondary surface mineralogy and fluid chemistry upon phase seggregation and fluid mixing." *University of Iceland,* Reykjavik, (2010), 1-61

Braddock, M., Biggs, J., Watson, I. M., Hutchison, W., Pyle, D. M., & Mather, T. A. "Satellite observations of fumarole activity at Aluto volcano, Ethiopia: Implications for geothermal monitoring and volcanic hazard." J*ournal of Volcanology and Geothermal Research,* 341, (2017), 70–83.

Brandmeier, M., Erasmi, S., Hansen, C., Höweling, A., Nitzsche, K., Ohlendorf, T., Wörner, G. "Mapping patterns of mineral alteration in volcanic terrains using ASTER data and field spectrometry in Southern Peru." *Journal of South American Earth Sciences,* 48, (2013), 296–314

Clarke, M. C. G., Woodhall, D. G., Allen, D., & Darling, G. "Geology, volcanological and hydrogeological controls on the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya." Ministry of Energy of Kenya, Nairobi (1990), pg. 138.

Eldosouky, A. M., Abdelkareem, M., & Elkhateeb, S. O. "Integration of remote sensing and aeromagnetic data for mapping structural features and hydrothermal alteration zones in Wadi Allaqi area, South Eastern Desert of Egypt". *Journal of African Earth Sciences,* 130, (2017), 28–37. https://doi.org/10.1016/j.jafrearsci.2017.03.006

Frutuoso, R. "Mapping hydrothermal gold mineralization using Landsat 8 data. A case of study in Chaves license, Portugal." *University of Porto,* (2015), pg. 85.

Hunt, G. R. "Electromagnetic radiation-the communication link in remote sensing; In: Remote Sensing in Geology". New York, *Wiley,* (1980).

KenGen. "Geological, Structural and Hydrogeological Mapping of the Eburru-Marulla-Badlands Geothermal Prospect-Phase II" *Kenya Electricity Generating Company – KenGen*. (Internal Report), Naivasha, 2018, 1–53

Lillesand, T., Kiefer, W. R., & Chipman, J. "Remote Sensing and Image Interpretation" *John Wiley & Sons, Inc,* Danvers, (2015), 1-720

Mia, B., & Fujimitsu, Y. "Mapping hydrothermal altered mineral deposits using Landsat 7 ETM+ image in and around Kuju volcano, Kyushu, Japan." *Journal of Earth System Science,* Kyushu, 121 (4), (2012), 1049–1057. https://doi.org/10.1007/s12040-012-0211-9

Munyiri, S. K. "Structural mapping of Olkaria Domes geothermal field using geochemical soil gas surveys, remote sensing and GIS" *UNU Geothermal Training Programme,* Reykjavik (2016), 1-64.

Onywere, M. S., Mironga, M. J., & Simiyu, I. "Use of Remote Sensing Data in Evaluating the Extent of Anthropogenic Activities and their Impact on Lake Naivasha, Kenya." *The Open Environmental Engineering Journal,* 5, (2012), 9–18. https://doi.org/Open access

Pour, A. B., Hashim, M., & van Genderen, J. "Detection of hydrothermal alteration zones in a tropical region using satellite remote sensing data: Bau goldfield, Sarawak, Malaysia." *Ore Geology Reviews*, 54, (2013), 181–196.

Rowan, L. C. "Near Infrared iron absorption bands: Applications to geologic mapping and mineral exploration" *In Remote Sensing*, 3, Watson and Regan, (1983).

Singh, A., & Harrison, A. "Standardized principal components". *Int. J. Rem. Sens*, 6(6), (1985), 883–896.

Van der Meer, F., Hecker, C., van Ruitenbeek, F., van der Werff, H., de Wijkerslooth, C., & Wechsler, C. "Geologic remote sensing for geothermal exploration: A review." *International Journal of Applied Earth Observation and Geoinformation*, 33, (2014), 255–269. https://doi.org/10.1016/j.jag.2014.05.007

Wendy, M. C., & Coolbaugh, M. "Application of remote sensing technology to geothermal exploration." *Great Basin Center for Geothermal Energy (GBCGE) and the Department of Geological Sciences*, 1(1), (2005), 083–1089.

Yetkin, E. "Alteration Mapping by Remote Sensing: Application to the Hasandag-Melendiz Volcanic Complex" *Middle East Technical University*, Ankara, (2003), 1-97