Monitoring of Thermal Variations in Geothermal Activity in the Mount Sirung Field, East Nusa Tenggara with Satellite Imageries

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Abstract. Mount Sirung Geothermal Field is one of the geothermal potentials that will be developed by the State Electricity Company (PLN) with a planned capacity of 5 Mwe. Geologically, Mount Sirung is located in a location with active volcanism and tectonism. In the context of exploration, knowledge is needed about the influence of volcanism and tectonism activities on geothermal fluid flow. The research was conducted with a *remote sensing* approach using ASTER Thermal Infra-Red (TIR) images acquired at night to monitor thermal variations through land surface temperature (LST) followed by analysis of high-resolution visible images (SPOT images) and Landsat 8 to determine the distribution of hydrothermal alteration for ten years (2011-2022). The results of this study show that there are changes in thermal variations and the distribution of hydrothermal alteration associated with volcanism and tectonism activities.

Keywords: *geothermal, remote sensing, mount sirung, tectonism, thermal variations, volcanism*

1 Introduction

Mount Sirung Geothermal Field, located on Pantar Island, is regionally included in the Lesser Sunda Islands group which is located in the transition zone between two active subduction ridges, namely the Sunda Arc and the Banda Arc. The Sunda Arc is a very steep and deep subduction zone, while the Banda Arc is relatively shallow and sloping with an average subduction speed of both subduction zones around 25 mm/year. Due to the difference in the direction of subduction of the Indian-Australian plate against the Sunda and Banda Arcs, two thrusting zones, namely the Flores Trust Zone on the Sunda Arc and the Wetar Trust Zone on the Banda Arc, occur. The difference in speed and direction of subduction causes the Lesser Sunda Islands to occur oblique subduction which produces an *en echelon* structure [1]. As a form of pressure accumulation over the subduction that occurred, the Lesser Sunda Islands formed sinistral en echelon fractures and rift zones which caused the formation of permeability which became a way for magma to come to the surface as a result of the partial melting subduction process. This causes Pantar Island to have high volcanic activity

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characterized by the presence of eight active volcanoes. In relation to the Mount Sirung Geothermal Field, the geothermal system of Mount Sirung is interpreted to consist of two sectors, namely the Sirung-Beang sector and the Airmama-Kuaralau sector. The Sirung-Beang sector is a volcanic, high terrain, high enthalpy and liquid dominated geothermal system [2].

According to seismic activity, based on the website(www.vsi.esdm.go.id) Mount Sirung is included in the medium category with the potential for earthquake shaking on an intensity scale of VII-VIII MMI. Then in the data obtained from BMKG (www.repogempa/bmkg.go.id) during the last 10 years (2011-2022) on Pantar Island at least 197 earthquakes occurred. The depth of the earthquake varies, some occurring shallow and some deep. Earthquakes with deep sources are indicated to have a connection with the Flores Thrust Zone [3]. Based on the frequency of earthquake occurrence, it can be concluded that the seismic activity on Flores Island is quite high. Meanwhile, in terms of volcanic activity, Mount Sirung is classified as an active volcano system where its last eruption was recorded on May 12, 2012 and in July 2015 it emitted thick smoke with a height of 500 m above the crater rim.

Geothermal fields associated with volcanic activity and active tectonic settings or seismically active areas will produce variations in geothermal system characteristics such as geochemistry and temperature. These characteristic changes are caused by subsurface chemical-physical processes such as fluid mixing, micro fracturing, and permeability changes [4]. Changes in the characteristics of the geothermal system above can be observed from changes that occur in thermal springs, altered rocks and epithermal mineralization that appear due to permeability zones. One method that can be used to approach changes in thermal anomalies is with the ASTER satellite sensor which stands for Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Land Surface Temperature (LST) and is supported by seismic data that occurs in the research area taken from a certain time. Based on these three data, we will see changes in thermal anomalies on the surface of the research area which are then connected to the point of seismic activity and the point of exploitation whether the anomaly occurs at that point.

2 Material and Method

2.1 Study Area

2.1.1 Regional Tectonics

Island is one part of the Nusa Tenggara Islands, which is located east of Java

Island. From west to east, this group consists of the islands of Bali, Lombok, Sumbawa, Sumba, Flores, Timor, Alor and Wetar. In terms of geodynamics, the Nusa Tenggara islands are located on the boundary between the Indo-Australian plate and the Eurasian Plate. In terms of tectonics, it consists of four tectonic units (from north to south), namely the Back Arc Unit (Bali and the Flores Sea), the Inner Arc Unit (consisting of volcanic islands from Bali to the west to Wetar Island), the Outer Arc Unit consisting of non-volcanic islands of Sabu, Dana, Rote and Timor Islands and the Front Arc Unit consisting of the Lombok Basin and Savu Basin. Stratigraphically, the Nusa Tenggara Islands consist of volcanic sedimentary rocks formed from subduction processes and are getting younger towards the east. The interesting thing is that the subduction of the Indo-Australian plate meets the subduction of the Australian plate with different directions and velocities resulting in an en echelon structure on Flores Island. This resulted in different volcanic activities along the archipelago including the cessation of volcanism on the islands of Alor and Wetar [5].

As mentioned earlier about the Nusa Tenggara Islands, also referred to as the Lesser Sunda, most of the islands included are volcanic islands or have active volcanoes. These volcanic islands are formed in a W-E aligned direction and form a magmatic arc called the Sunda-Banda Arc (**Figure 1)**.

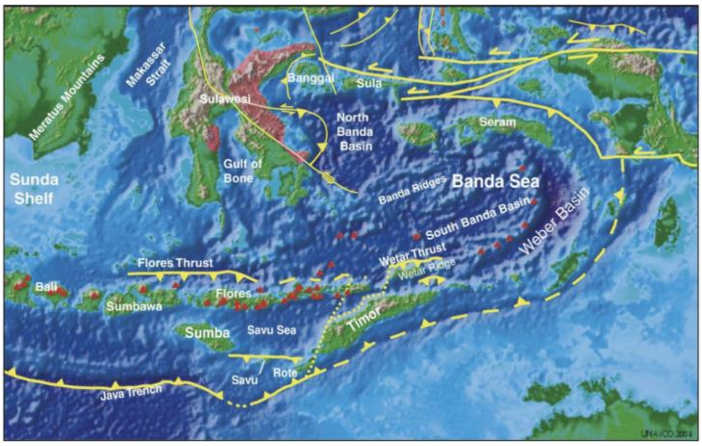


Figure 1 *Tectonic condition of Eastern Indonesia, focus on East Sunda-Banda Arc [6]*

The processes that occur in the Lesser Sunda are quite complex which include several processes including subduction, which occurs between the Indo-Australian Plate and the Eurasian Plate which creates an archipelago of volcanic arcs on the edge of the Eurasian plate. Over time, this subduction turned into a collision between the Indo-Australian and Eurasian plates. This collision occurred due to changes in the geometry and direction of subduction. The Australian plate, which is part of the Indo-Australian plate, began to collide with the volcanic arc that had formed. As a result of this collision, several events occurred, among others: Thrust Faulting or the formation of rising faults that form mountains on the islands of Timor and Sumba, folding that forms complex structures, accretionary wedges, namely the removal of sediments and rocks in the subduction zone, and the formation of basin formations such as the Lombok and Savu basins. In addition to this, the result of the collision process is the occurrence of volcanism and magmatism activities that are quite intensive. As a result of compression forces, melting of mantle and crustal rocks occurs, resulting in volcanic eruptions and intrusions. However, there are differences between each part of the arc, some produce active volcanism while other parts also experience a decrease in volcanic activity such as on Alor and Wetar Islands [6].

2.1.2 Regional Stratigraphy

Based on the Regional Geological Map of Lomben Sheet, Pantar Island is found as one part of Lomben Island which is composed of six main lithological units from old to young as follows [7]:

1. Granodiorite Intrusion (Tmgd), the age of this intrusion is estimated to be Late Miocene;
2. The Alor Formation (Tmpa), the age of this formation is estimated to be Late Miocene to Early Pliocene and consists of lavas, breccias, tuffs of sandy silt;
3. Old volcanic rocks (QTv), the age of this formation is estimated to be Pleistocene and is composed of lava, agglomerate breccia, tuff, volcanic sand, and claystone passive tuff;
4. Coral limestone (Ql), composed of coral limestone;
5. Young Volcanic Rocks (Qhvt), the age of this formation is estimated to be Holocene and is composed of lava, agglomerates, bombs, pebbles, sand and volcanic ash;
6. Aluvium (Qal), the age is recent and is composed of crusts, pebbles of andesite, diorite, basalt and granodiorite, sand, silt and mud.

2.1.3 Geological Structure

In general, the structure that occurs on Pantar Island is a result of the subduction process of the Indo-Australian Plate with the Eurasian Plate where this subduction ends as a collision. The main geological structures that develop are caused by, among others, rising faults in the north of Flores to Wetar (Flores Thrust and Wetar Thrust), troughs in southern Timor (Timor Trough) and sinistral shear faults on Pantar Island and Alor which are referred to as Pantar Fracture [2].

In general, in Eastern Indonesia, there is quite complex tectonic activity due to the clash of four plates namely Australia, the Pacific, the Philippine Sea Plate, and the Sunda Block. The Australian Plate subducts northwards from the east of Java to Nusa Tenggara and the Banda Arc. Where the three meet as a transition between continental-oceanic plate collision in eastern Java, volcanic arc and continental plate collision in Nusa Tenggara and island arc collision in the Banda Sea. However, when it comes to seismic activity not much data has been recorded, only at least seven major earthquakes occurred between 1648 and 1891, four of which were major earthquakes that caused tsunamis in the Flores Sea [8].

2.1.4 Hydrothermal Alteration

In Gunung Sirung Geothermal Field, alteration caused by geothermal activity or hydrothermal alteration occurs which produces minerals including silica, kaolinite, gypsum, clay minerals, jarosite, goethite, hematite, and carbonate. These alteration minerals are found in the field in andesite lava, basalt lava, pyroclastic breccia, and tuff rocks with an indication of alteration levels between 5%-100%. The hydrothermal alteration is found due to the process of replacement, leaching, and direct deposition [2].

2.2 Material

2.2.1 Primary Data

In this study, the primary data used were sourced from images of three satellites, namely:

a. ASTER from Terra Satellite (AST_08 Surface Kinetic Temperature) especially using its thermal band,
b. Satellite Pour I'Observation de la Terre (SPOT) 4,5,6 and
c. Landsat 8, L1TP (Collection2 Level 1) especially band 2 to 8.

The images were taken in the range of 2011 to 2022 with the consideration of knowing the changes in thermal variations in the geothermal field of Mount Sirung due to the process of volcanism and tectonism where the last eruption year of Mount Sirung (2012) was taken one year before the eruption until the acquisition of field data by researchers in 2022 to find out the conditions in the field. ASTER-TIR imagery considered its good spatial resolution of 90 m and the imagery used was nighttime acquisition imagery to minimise the temporal variation of sunlight heat. SPOT imagery was used in consideration of its good spatial resolution: SPOT 4 is 10 metres, SPOT 5 is 2.5 metres and SPOT 6 and 7 are 1.5 metres (after panspectral sharpening). The Landsat 8 image data acquisition was taken relatively in July-September where the cloud coverage level is quite low (0-15%).

2.2.2 Secondary Data

Secondary data used in this study include lithological data, alteration minerals and geological structures from previous studies, seismicity data obtained from Badan Meteorologi dan Geofisika (BMKG) and volcanism activity data obtained from Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG).

2.3 Method

2.3.1 Research Methods

In general, this research was carried out in stages starting from literature study, data acquisition, pre-processing to evaluation as in the flow chart below (Figure 2).

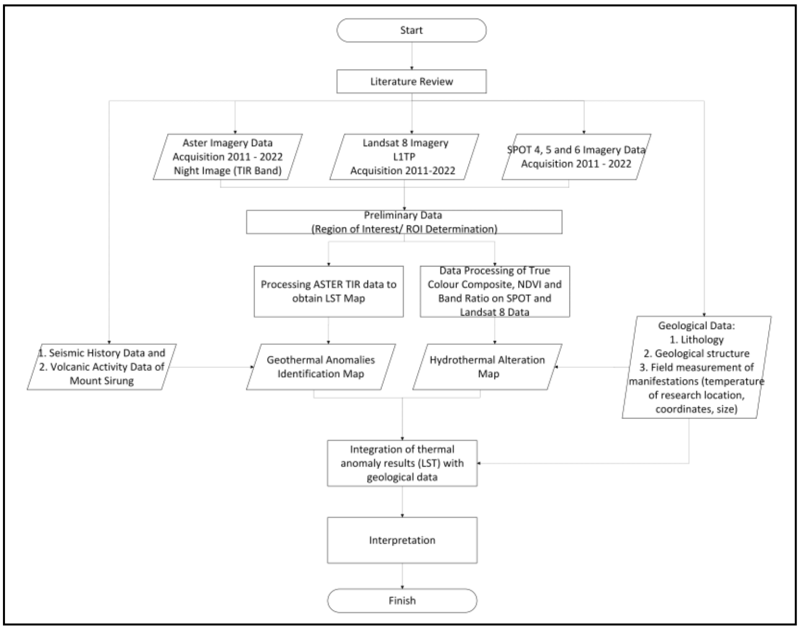


Figure 2 Research Method

2.3.2 Image Processing

In this research, Landsat 8 image data will be processed in 5 stages. The first stage is image reprojection from the WGS 1984 51 N (Northern Hemisphere) system to WGS 1984 51 S (Southern Hemisphere) because the research area is located in southern latitudes. The second stage is radiometric correction. Previously, the Landsat 8 Collection 2 Level 1 has been geometrically and topographically corrected due to the position of the satellite during image capture, the height and angle of recording and the surface altitude [9], so no geometry correction was done again. Radiometric correction is performed to convert electromagnetic wave recording results (Wm-2sr-1μm-1) into pixel values (digital numbers). Because during the journey of electromagnetic waves from the object to the satellite through atmospheric disturbances, correction is needed to improve the pixel value read from the atmospheric disturbance [10]. The formula used to perform radiometric correction is as follows:

$$\rho\lambda = \frac{M_\rho \cdot Q_{cal} + A_\rho}{\sin(\theta se)}$$

Where,
$\rho\lambda$ = Top of Atmosphere;

M_ρ = rescalling constraint [REFLECTANCE_MULT_BAND_X, where x is the band used];

Q_{cal} = pixel value (DN);

A_ρ = enhancer constant [REFLECTANCE_ADD_BAND_X, where x is the band used];

θse = sun elevation angle at the time of recording (sun elevation) obtained from the image header.

The third stage is the preparation of the True Colour Composite with a 4-3-2 multispectral band composition (Table 1). The multispectral band has a resolution of 30 metres (Table 1), while the pan spectral band has a resolution of 10 metres. In order to obtain an image with a better resolution, a pan sharpening process of the band 4-3-2 composite image with band 8 was performed.

Table 1 Summary of band and bandwith of Landsat 8 [10]

Band	Bandwidth (μm)		Resolution	Application
1	0,433 – 0,452	Ultraviolet	30 m	Coastal, aerosol
2	0,45 – 0,515	Blue	30 m	Visible
3	0,525 – 0,600	Green	30 m	
4	0,630 – 0,680	Red	30 m	
5	0,845 – 0,885	VNIR	30 m	Vegetation analysis
6	1,560 – 1,660	SWIR 1	30 m	
7	2,100 -2,300	SWIR 2	30 m	
8	0,500 – 0,680	Panchromatic	15 m	Better resolution
9	1,360 -1,390	Cirrus	30 m	Cloud analysis
10	10,5 -11,2	Thermal	100 m	Earth temperature
11	11,5 – 12,5	Thermal	100 m	

The fourth stage is the calculation of Normalized Difference Vegetation Index (NDVI) to determine the level of vegetation density. This value is derived from the specific absorption rate of red-edge by chlorophyll and plant stomata. Points with high NDVI values represent vegetation density while points with low vegetation have NDVI values close to 0. This occurs due to the reflection of the wavelength used in the NDVI equation from the relatively constant soil. Generally, the value of points covered by vegetation ranges from 0.1 -0.6 [10]. The equation used is:

$$NDVI = \frac{\alpha_{NIR} - \alpha_{VIS}}{\alpha_{NIR} + \alpha_{VIS}}$$

where,

α_{NIR} = reflectance value at red wavelength ~0,6 μm (band 4)

α_{NIR} = reflectance value at near infrared wavelengths ~0,8 μm (band 5)

The fifth stage is band ratio analysis to map the hydrothermal alteration area. As known in previous studies, the Mount Sirung area has alteration of silica, kaolinite, gypsum, clay minerals, jarosite, goethite, hematite, and carbonate [2]. In order to map these alteration minerals, a false colour composite with a band ratio of 4/6-4/2-6/7 was used. This band ratio aims to determine the distribution of alteration of iron and clay minerals due to hydrothermal processes [11].

3 Results and Discussion

The analysis was conducted on Landsat 8 images for four years, namely 2013, 2014, 2015 and 2016. This was done because there was limited Landsat 8 image data for the years 2011 and 2012, there were no images good enough to be analysed. So that the image was taken in these four years to find out any changes in the alteration zone from before and after the increase in volcanic activity in 2015.

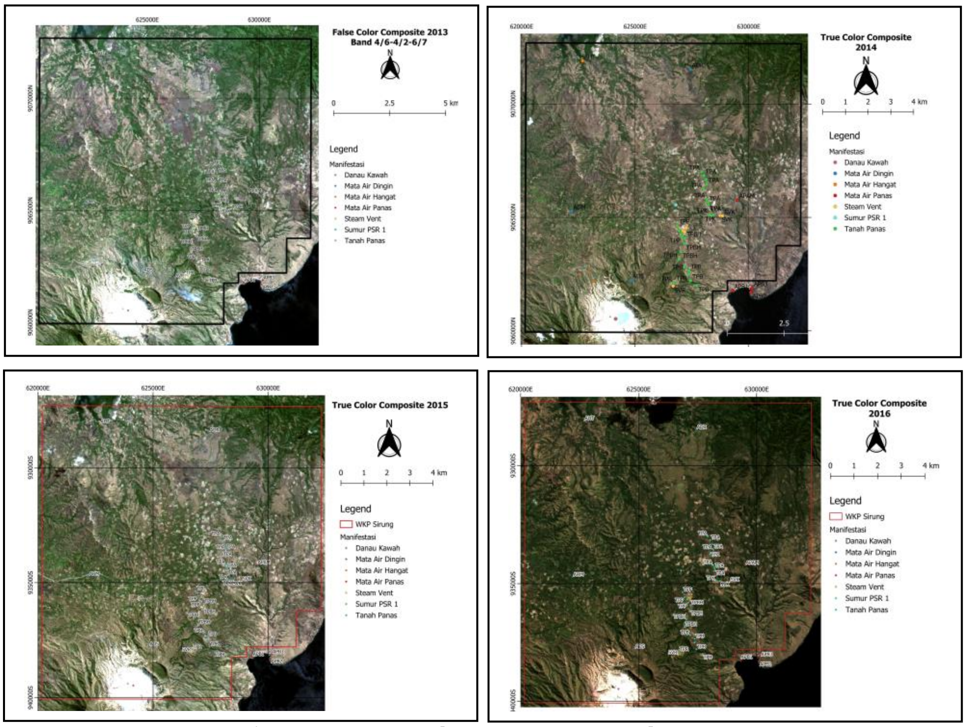


Figure 3 *True Color Composite Band 4-3-2*

The image above is a true colour composite band 4-3-2 image from Landsat 8 in the years (from top left to bottom right) 2013, 2014, 2015 and 2016 (Figure 3). This image can help in eliminating areas that will be read in subsequent analyses as having no vegetation but are actually residential or agricultural areas.

The image processing results for NDVI values in the four years above show variations between one year and another but not significantly (Figure 4). This can be seen from the range of NDVI values from year to year. In 2013 the NDVI value was -0.27 to 0.855. In 2014 the NDVI value ranged from -0.258 to 0.8411. In 2015 the NDVI values ranged from -0.822 to 0.840 and in 2016 the NDVI values ranged from -0.76 to 0.878. While on the map there is a change in points covered by good vegetation (green colour) and those that are not (red colour). In 2014 and 2015, especially around the neighbourhood of Mount Sirung (blue circled zone).

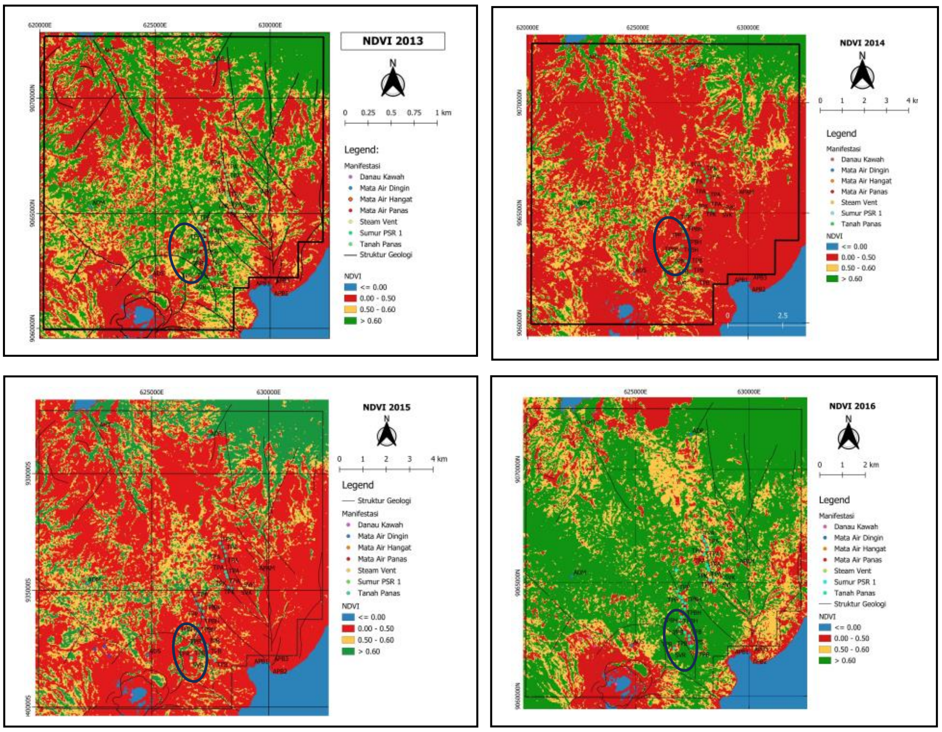
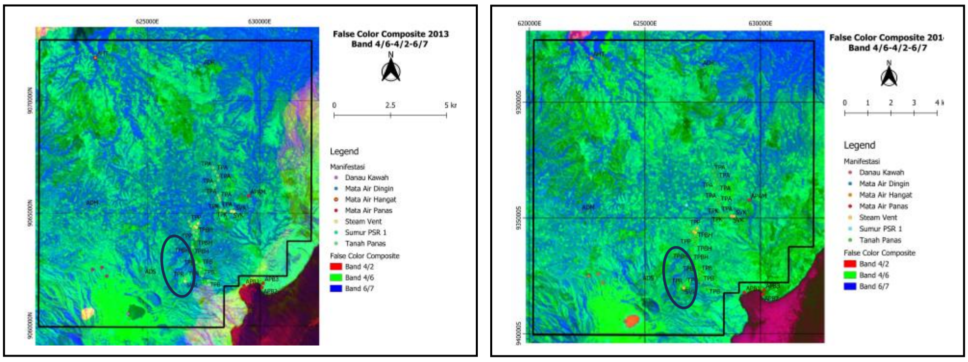


Figure 4 NDVI Map



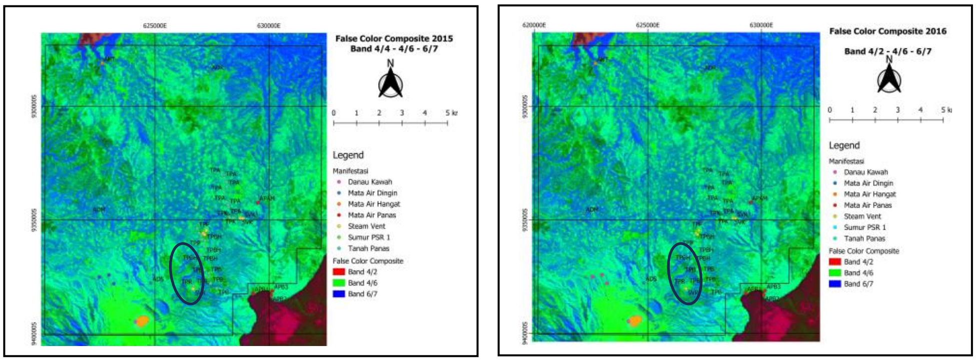


Figure 5 *False Color Composite Band Ratio 4/6-4/2-6/7*

The false colour composite (FCC) map is then created by juxtaposing band ratio 4/6 as band 1, band ratio 4/2 as band 2 and band ratio 6/7 as band 3 (Figue 5). Band ratio 4/2 indicates the presence of iron minerals which are products of hydrothermal alteration while band ratio 6/7 indicates the presence of alunite, illite kaolinite and montmorillonite which are also the result of hydrothermal alteration [11]. Therefore, the FCC map below shows that the lighter green colour is interpreted as the presence of iron oxide minerals and the blue colour indicates the presence of alteration clay minerals. When viewed from year to year, after 2015 in the area around the crater of Mount Sirung there is a further spread of alteration minerals, especially in the area near the ASM, APAM' and APAM manifestations (blue circled zone). This is interpreted as a result of increased volcanic activity in 2015.

Analysis was also carried out on night acquisition ASTER TIR images. Unfortunately, in 2013, 2014 and 2016 the cloud coverage was high enough to under-represent the surface temperature conditions. In Figure 6, there is a match between the zone with relatively high temperature (yellow-red) and the zone of manifestation and alteration.

4 Conclusion

Based on the above results, it can be temporarily concluded that volcanism activities can affect the distribution of hydrothermal alteration that occurs, which means that the geothermal system is also affected due to these activities. Additional data is needed to confirm whether other than volcanism activity also influences changes in the flow of geothermal fluids. As a suggestion, it is necessary to analyse more images in the year before and after and equipped with a surface temperature map to confirm whether the alteration zone that has been mapped really has a temperature above the ambient temperature.

5 Discussion

Based on the results of the above study, there are still shortcomings in terms of comparison between surface temperatures (LST) from year to year. So it is strongly recommended to reacquire by taking into account the seasonal equation so that seasonal temperature variations do not affect the analysis and test more years so that changes can be clearly illustrated over a longer period of time.

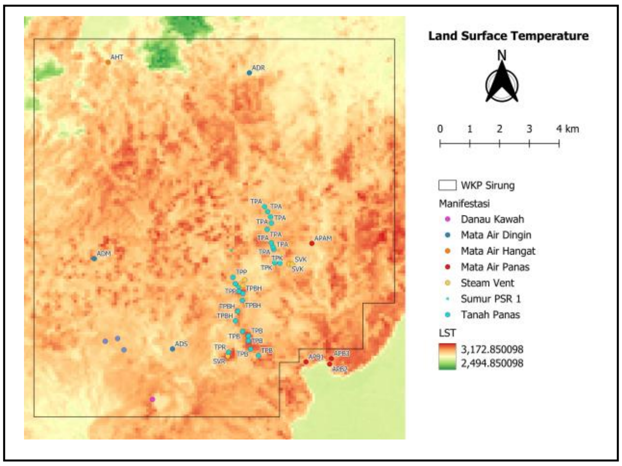


Figure 6 *Land Surface Temperature*

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