APPLICATION OF THERMAL REMOTE SENSING TO THE INDONESIAN LUSI ERUPTION

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ABSTRACT

Lusi (contraction of Lumpur Sidoarjo), is a relatively recent sediment-hosted geothermal system located in the Sidoarjo Regency in East Java, Indonesia. The eruption started on May 29, 2006 in the middle of a highly populated area. Economic losses due to the disaster have been estimated at more than $4 billion USD and 60,000 people had to be evacuated from their flooded homes. The volcano is still active and a variety of surveys are routinely carried out to provide a better understanding of the Lusi hydrothermal plumbing system.

In this work we provide the first remotely sensed thermal characterization of Lusi volcano at moderate (90m/px) spatial resolution. We accessed and processed a large collection of ASTER L2 TIR Surface Radiance images (AST_09 product) acquired over the period 2006 to 2014. For this study, night-time cloud-free data were selected. The images have been converted to kinetic temperature, by inversion of Plank function, in order to provide an estimate of the hot-spot kinetic temperature. The temperature has been calculated for ASTER Band 13 10µm). An emissivity value of 0.98 was derived using reflectance. The spectrum has been measured on a sample acquired during the November 2014 multidisciplinary fieldwork as part of the LUSI LAB project (CEED, University of Oslo). During the survey we also used a thermal infra-red (TIR) camera to acquire in situ temperatures to be compared to TIR data from a predicted ASTER overpass. Here, we provide the first remote-sensing-derived time series of Lusi crater thermal behaviour. Although the overall trend is constant, minimum values are present in 2008, 2010, 2013 and 2014. A Pearson correlation of the temperature (average over year between 2008-2014) against the number of cracks that appeared during the period of investigation, resulted in a 0.72 correlation. Decorrelation stretching of TIR surface radiance images has been used to locate mineral alteration induced by bubbling hydrothermal activity.

INTRODUCTION

Lusi (contraction of Lumpur Sidoarjo), is a relatively recent sediment-hosted geothermal system (“mud volcano”) located in the Sidoarjo Regency in Northeast Java, Indonesia. It erupted on May 29 2006 resulting in a natural disaster with a great economic and social impact. Economic losses have been estimated to be more than $4 billion USD, with 60000 evacuees from flooded homes (1).

Although the phenomena was initially attributed to a drilling operation (2). other studies (3, 4, 5), conclude that Lusi is a natural event triggered by the Yogyakarta earthquake that occurred 47hrs before the eruption.

The size and duration of the Lusi activity make it of great interest for both scientists and government institutions which have to deal with the environmental, social, and economic impact.

Traditional exploration methods to study geothermal systems such as Lusi, use geochemical and geophysical approaches (6). Geochemical surveys focus on the collection of sample water (7) from hot springs, gas from hot pools and steam from fumaroles where the fluid chemistry can be used to develop geothermometers that provide an estimate of the temperature of deep reservoirs (6).

Multiple scale remote sensing techniques, ranging from in situ near-field to satellite efforts, can provide valuable contributions to geothermal system mapping. For example, multispectral broad-band remote sensing can be used to map broad classes of surface mineral facies (6), while imaging spectroscopy produced by hyperspectral instrumentation can be used to make mineralogy maps (7, 8, 9), and to quantify gas emissions (10, 11). Interferometric SAR (Synthetic Aperture Radar) instruments allow the monitoring of subsidence and surface deformation (12).

Although longwave infrared remote sensing has been used to monitor thermal anomalies and for lava flow characterization of volcanoes, it has seldom been applied to the study of geothermal systems. Major reasons for this have been the spatial resolution limitations of available thermal satellite data (e.g., ASTER: 90-100m/pixel), and very high cost of airborne operated systems, with which to improve the spatial resolution. Although the such limitations apply, a number of studies have been conducted using TIR data to map the surface temperature, and to correlate that to the geothermal vigor (e.g.13, 14,15, 16), all based on analyses of ASTER TIR bands.

The current study aims to investigate if and how remotely sensed thermal data can support the understanding of Lusi short-long term behaviour. Within this study, we have used satellite and in situ data. At satellite scale we have selected ASTER night time-series data from 2006 to 2014. We have derived a temperature map and traced the temperature behavior of the crater over the last 8 years. Furthermore we have used the satellite scenes also to study a possible correlation between temperature and highly active seeps and vents (exhibiting hydrothermal bubbles).

METHODS **Satellite methods:** ASTER night

In order to understand the long-term (seasonal-year) temperature variability of Lusi ASTER TIR nightime data have been analyzed. We have selected 30 Lusi cloud-free imagery over 8 years (2006-2014). We used the Level 2 AST_09T ASTER product (17) which consist of atmospherically corrected surface radiance. The images have been converted to kinetic temperature by inversion of the Plank function (18), to provide an estimate of the hot spot kinetic temperature. The temperature has been calculated for ASTER Band 13 (10µm). An emissivity value of 0.98 has been derived by using reflectance measured on Lusi sample acquired during the November 2014 fieldwork. The temperature variation of the hot spot (Lusi Crater) has been compiled into a time series, and the position of the main crater has been tracked, in order to assess any potential crater migration. Active seeps have been studied by investigating temperature anomalies and mineral alteration. To address the mineral alteration we have applied a decorrelation stretch to the surface atmospherically corrected radiance image, as described by Gillespie, (19).

Field method: crack distribution and bubbles

The Lusi volcano is characterised by 100m diameter main active vent located approximately at the centre of the edifice. Numerous secondary vents (seeps) have been forming following the eruption and have been located by BPLS. In the first year of Lusi activity the vents activity was concentric and localised 1KM SW of Main crater (20). A couple of years later newer seeps clustered close to the Kendasari river to the west Lusi, More recent activity is concentrated on the West. The seeps localization is quite difficult because of limited access to the majority of the areas where they occur and because some has a short live. In figure 1 is plotted the number of active vents from 2008 to November 2014.

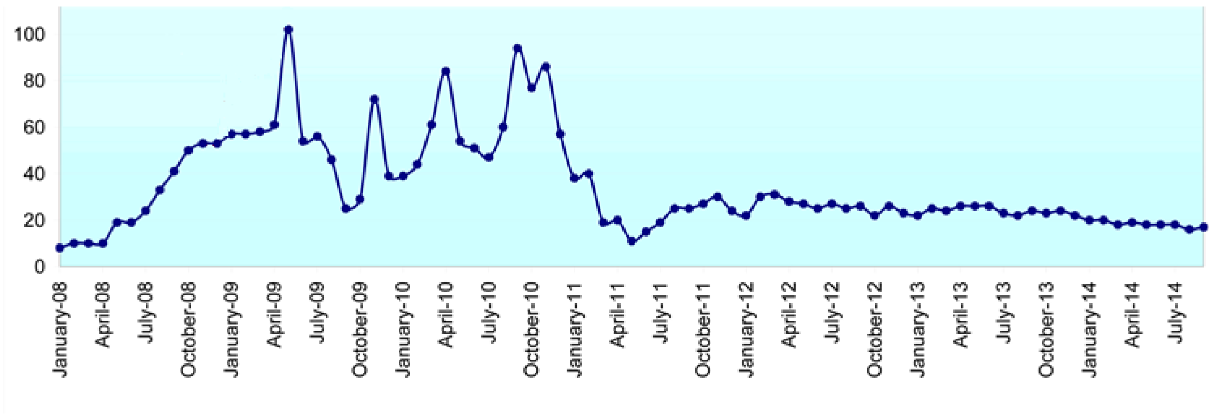

Figure 1: number of active seeps (y axis) from 2008 to November 2014.

RESULTS

Main vent temperature

We created a Lusi temperature map based on ASTER TIR data for . integrated temperatures over a 90mx90m pixel size. The Lusi central crater hot spot temperatures were recorded , with data displayed as the time averaged temperature (Figure 2a). The plot shows a constant overall trend with minimum temperatures on 10 July 2006 and 07 July 2013.

In Figure 2 b, the mean temperature, has been plotted for the dry season only. While the temperature increased during the first year of activity, the overall trend in the 8 years has been relatively constant. In 2a we see an oscillating min-max temperature change versus a fairly constant trend for 2010. The absolute minimum is registered during the dry season 2013.

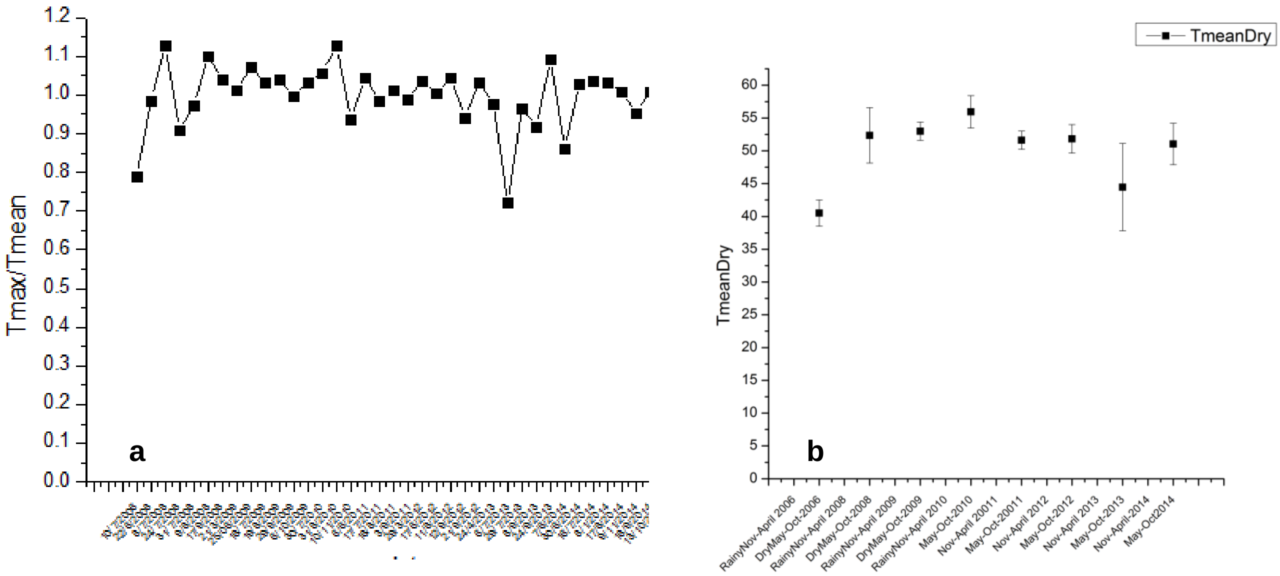

Figure 2 a) The temperature of the main vent has been normalized to mean value over the time series (T_{mean} =51.17degC). b) average temperatures for dry season have been plotted.

Also, a statistically significant correlation (Pearson's correlation coefficient, *r*=0.89) exists between hot spot temperature and the number of active vents in the last 8 years.

In figure 3 we show an example of thermal maps retrieved for July 2009 and September 2009. when an increase in seep activities in Peta area was detected.

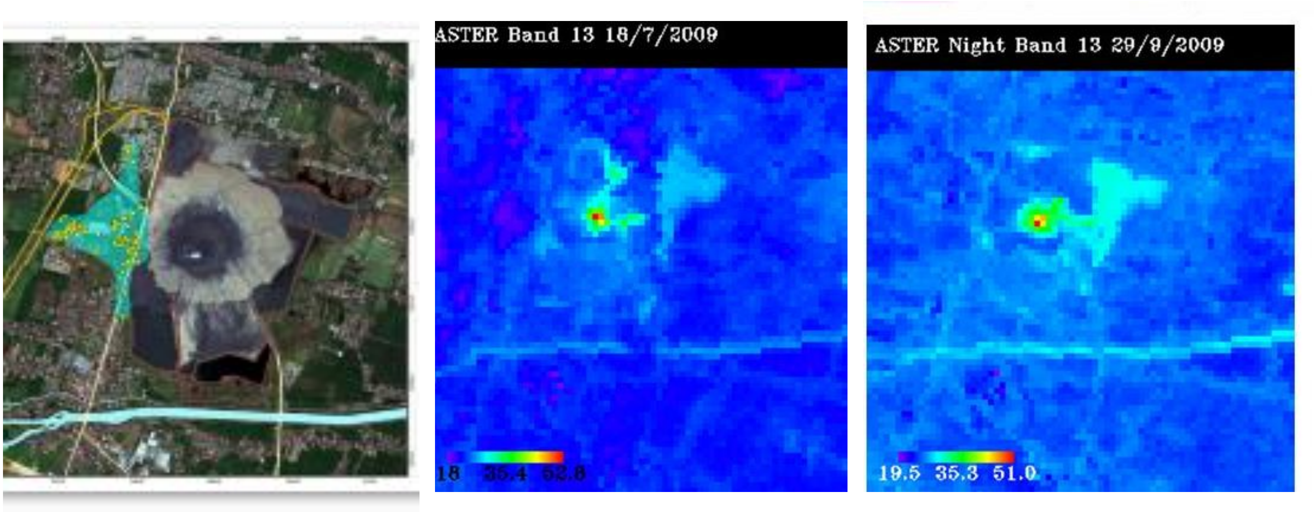

Figure 3. Locations of hydrothermal bubbling areas present in 2009 are superimposed on a high resolution satellite image from 16 August 2014 (far left). Temperature maps of ASTER TIR data from July and September 2009 show thermal anomalies in the Peta (central crater) area on 18 July and 29 September. A high percentage of water surface and river flow is seen as bright light blue in these false colour images, while the red hot spot shows the position of main vent (approx 50degC).

Mineral alteration due to hydrothermal pools and vents can be detected and mapping using at surface radiance. In particular, decorrelation stretching techniques (19) producing false colour composites are created by assigning primary colours to ASTER bands 13, 12 and 10. Figure 4 shows the hydrothermally altered pixels as dark violet.

Locations of satellite image alteration zone pixels (Figure 4a,b) have been plotted versus in situ measured locations of 2009 hydrothermal bubble zones (Figure 4c) showing a good agreement, within geolocation error. An interesting alignment of Alteration Zone 4 (in Figure 4b) with the Watukosek fault can be seen.

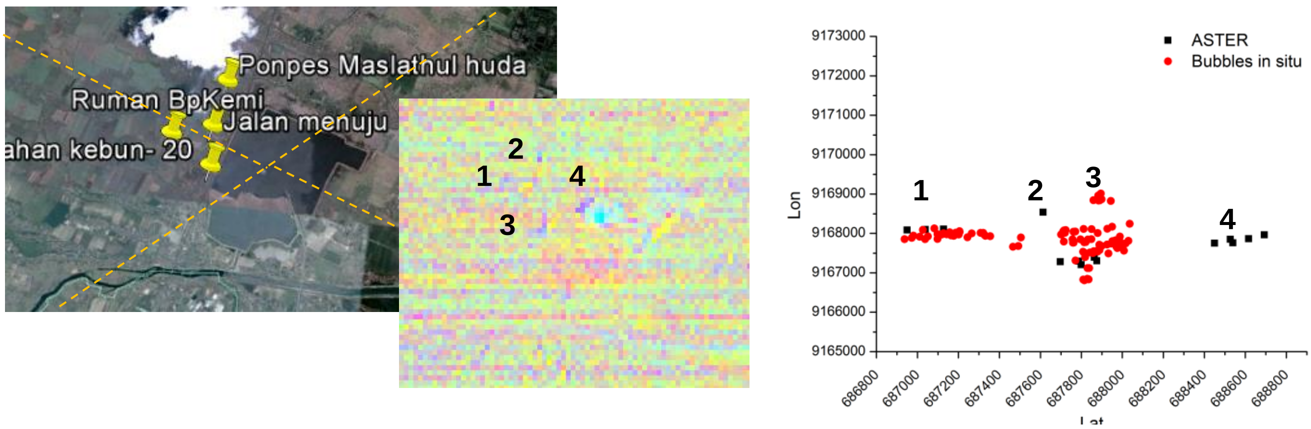

Figure 4 a) 23 September 2009 high resolution Google Earth image (Digital Globe) showing alteration zones determined by in situ field measurements; b) False colour composite RGB (ASTER band 13, band 12, band 10) showing hydrothermal alteration zones on 29 September 2009; c) comparison of hydrothermal bubble activity vs in situ determination of hydrothermal bubble zones and seeps for September 2009.

CONCLUSIONS

Night time acquisitions of ASTER thermal data from 2006 to 2014 have been analysed to investigate strategies to use high spatial resolution (90m/pixel, 8-12um) ASTER thermal remote sensing in the study of Lusi short and long term behaviour.

The overall trend of the main vent temperature appears to be constant over a period of about seven years. This implies that the stability time-scale of this feature is at least that long. The large size and relative stability of the Lusi feature over this timescale may indicate a connection with hydrothermal circulation systems that are relatively deep seated and related to major faults that transect and underlie the feature.

A significant correlation in terms of 0.89 Pearson's correlation coefficient between main vent temperature and hydrothermal bubble activity has been found. In particular, variation in main vent temperature (e.g. in the years 2009-2010) corresponds to an increase in number of active hydrothermal bubble sites.

Localtions of thermal anomalies and spectral analyses of at-surface radiance have been used to identify and characterize surface alteration due to hydrothermal .processes (e.g. bubble zone activities). In particular, a good agreement between ASTER TIR data (29 September 2009), hydrothermally altered pixels, and in situ thermal field measurements has been found. Furthermore, hydrothermally altered zones have been found to be aligned in the direction of the Watukosek fault.

Only preliminary reconnaissance results are reported, and future work will extend this study year-to-year. Currently analyses of in situ thermal activity and spectral reflectance measurements acquired during November 2014, as well as mineral composition studies will be reported in the near future.

ACKNOWLEDGEMENTS

We would like to thank Francesco Beccari, DIESSECHEM, for lending the HH2 ASD spectrometer used during the fieldwork. We thank Soffian Hadi and Prof. Dr. Hardi Prasetyo (BPLS), for their support during the fieldwork, and Prof. Sergio Pugnahi is thanked for valuable support in ASTER data temperature retrievals. This work was carried out, in part, at the Jet Propulsion Laboratory, under contract to NASA.

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