Remote Detection of Thermal Anomalies for Geothermal Exploration. How Well Does It Work?

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ABSTRACT

Surface manifestations are an indicative sign of the geothermal activity in the subsurface. By far not all geothermal systems develop surface manifestations but where they are present, they are a good starting point for early stage exploration efforts. Hence, it is crucial to have a technique that can successfully and reliably detect and map (and possibly monitor) surface manifestations. Remote sensing has the potential to support the mapping of such geothermal surface manifestations, including deposited and altered mineralization and temperature anomalies. In particular, thermal infrared bands of multispectral satellite sensors, for example, have been shown to be effective in detecting surface temperature anomalies in ideal circumstances. Practical experience with thermal infrared data, however, often shows a more complex situation: thermal anomalies appear subdued in satellite data with only moderate spatial resolution (e.g. ASTER @ 90 metres) and are not easily discriminated from false anomalies that are created by solar heating and differences in e.g. land cover, rock properties or soil/vegetation moisture. Night time acquisitions suppress these false anomalies only partially since the acquisition time of most satellite sensors (e.g. ASTER @ 10.30pm local time) is too early in the night for the temperatures of the surrounding strata to have reached an equilibrium. In this paper we highlight some of the factors that influence the process of anomaly detection, compared to ground to airborne temperature measurements of thermal anomalies in a controlled test site area. We also introduce the new higher spatial resolution and multi-temporal ECOSTRESS sensor (JPL/NASA) as a possible step forward in the future detection of geothermal temperature anomalies.

1. INTRODUCTION

Early stage exploration for new geothermal fields typically starts at sites where surface manifestations (e.g., hotsprings, fumaroles, mudpools; Figure 1) reveal geothermal activity in the subsurface. Spaceborne thermal infrared (TIR) sensors, e.g., NASA/JPL's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) or Landsat TIRS, can be used to detect thermal surface temperature anomalies (or "hotspots") associated with geothermal surface manifestations (Figure 2) from space. As an example, Coolbaugh et al. (2007) looked at geothermal anomalies in the Nevada Desert with ASTER data. Vaughan et al. (2012) used ASTER (amongst other sensors) to map geothermal anomalies and heatflux in Yellowstone national park. van der Meer et al. (2014) used ASTER over the Chilean desert to map alteration mineralogy as well as temperature anomalies.

Figure. 1: Example of a mud pool as a surface expression of subsurface geothermal activity. Mataloko, Indonesia. Diameter ca. 5 m.

However, detection of geothermal anomalies from spaceborne sensors appears restricted to the most optimal circumstances, where anomalies are large in size (compared to sensor's pixel size) and show considerably higher temperatures than the background values (Hecker et al., 2017). Even in less optimal cases (i.e., anomalies of a sub-pixel footprint, or with only mildly elevated pixel temperatures) anomalies should be detectable with modern sensors (i.e., appropriately lower Noise Equivalent Differential Temperature NEDT to such anomalies). Geothermal anomalies observed by such moderately sized satellite pixels, however, often don't sufficiently exceed the temperature variance of the background pixels (i.e., the range of pixel temperatures that are not related to geothermal elevated heat flux) to be detected. These issues need to be understood and tackled in order to maximize the usability of TIR satellite data in mapping of geothermal anomalies. In this paper, we look at some of the factors that influence the detection of these geothermal surface temperature anomalies.

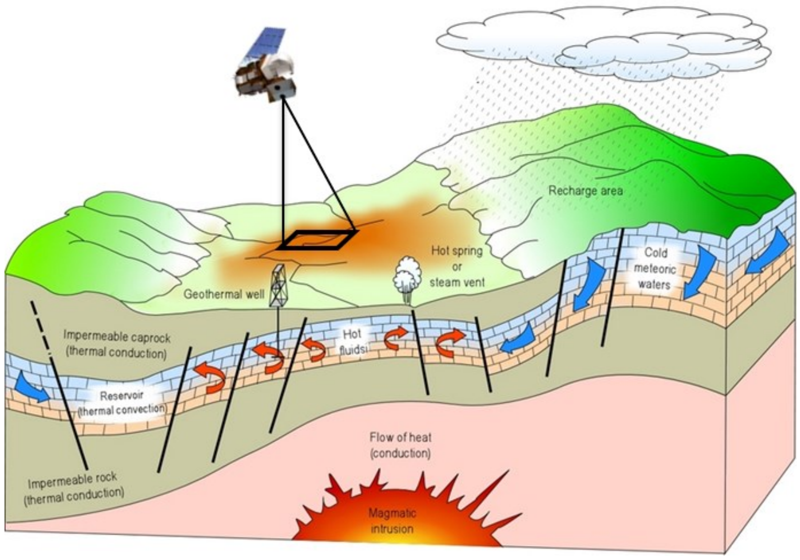

Figure 2: Typical volcanic geothermal system with a subsurface reservoir and its surface expressions. The use of spaceborne remote sensing, as a tool to investigate thermal surface anomalies is highlighted (black square). (After Dickson and Fanelli, 2004)

2. ANOMALIES NOT AS HOT

The anomalous surface temperature that we measure on the ground at surface manifestations are in fact not as hot on thermal infrared pixels as we would expect. The work of Ramdhan (2019) for example shows that even low altitude (1000m above ground) airborne data at .5m resolution shows significantly different results in the airborne data (thermal FLIR camera) as compared to ground radiant temperature measurement (Figure 3). The temperature range for the airborne measurements is strongly reduced and the correlation between the two measurements (airborne and ground-based) is low.

We expect that the main reason for this effect is related to a sampling bias of sub pixel dimensions. Geologists on the ground will use a radiant or contact thermometer and aim at the hottest objects, e.g. the fumarole opening in the ground. They will read a value close to 100C and assume that this would be the temperature that an imaging sensor would read as well. However, these high spatial resolution airborne datasets show that this is not the case. By convolving the airborne data to lower spatial resolution of a satellite sensor (e.g. 90m for ASTER), a first approximation of the pixel integrated temperature at that spatial resolution can be simulated. Naturally, averaging temperatures over larger pixels will further decrease the temperature contrast between anomalies and background temperatures.

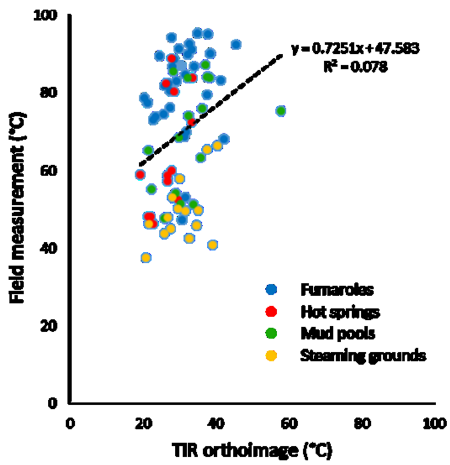

Figure 3: Scatterplot showing ground measurements with radiant thermometer (y-axis) measuring about a 5 cm diameter area, against the corresponding pixel temperature in the 0.5 m resolution airborne FLIR camera data (x-axis). The colour coding shows different styles of surface manifestations measured. The dashed line is a regression line of the data cloud. Results show that steaming grounds with large extent are closest to their respective ground measured temperatures, and fumaroles (with small vents surrounded by colder temperatures) are furthest away. From Ramdhan (2019).

3. ANOMALIES NOT AS ANOMALOUS

At the pixel size of a spaceborne sensor (e.g. ASTER), the pixel integrated temperature of an anomalous pixel is not as anomalous as we may think and true anomalies are often swamped out by elevated surrounding temperatures in the image that are caused by non-geothermal effects. This high variance in the background makes a reliable assignment of elevated measured temperatures to a geothermal source a challenge. High variance of background temperatures is caused by material properties, such as heat capacity (Kahle 1987) and its associated thermal inertia) and albedo, but also by the surface orientation in relation to the incident solar radiation. Exposure to the sun causes solar forcing which increases the ground temperature. This effect is stronger for materials with high absorbance (e.g. low reflectance) and surfaces which are oriented perpendicular to the insolation direction. After sunset, solar forcing stops and surfaces try to reach equilibrium, which can take hours depending on heat capacity, emissivity of the materials and ambient conditions, and may not even reach equilibrium before sunrise (Coolbaugh et al., 2007).

Most sun-synchronous platforms have a descending orbit that passes during early night when materials are still far from reaching temperature equilibrium. For thermal hotspot detection the ideal acquisition time is pre-dawn, just before solar forcing starts again. By then temperatures have stabilized as much as possible which reduces the variance of the background temperatures and enhances potentially geothermal related pixels.

4. OTHER FACTORS

Additional disturbing factors are vegetation cover, vegetation and soil moisture content and atmospheric gas interferences. Dense vegetation cover naturally blocks the radiation coming from the ground. However, warm air rising through the canopy may potentially be detected at high spatial resolution and in still conditions. Mixed vegetation / soil cover with moisture content also influences the thermal response either through the cooling effect of their evapo-transpiration or the thermal inertia properties above the water content itself in such ground cover.

Fumaroles and steaming ground also release water vapour and other gases that are infrared active. They absorb (i.e. block) as well as re-emit IR radiation. However, re-emission happens at the energy levels of the atmosphere rather than the ground. Hence, above a steaming mud pool of 100C, we rather measure the much lower air temperatures tens of meters in the atmosphere than the boiling mud pool on the ground.

5. POSSIBLE SOLUTIONS

In the past, researchers have tried to reduce the effect of the background variation relative to geothermal anomalies with the help of e.g. band ratios (e.g. Hecker et al., 2007), daytime / nighttime pairs to model heat capacity (e.g. Coolbaugh et al., 2007) by empirical modelling of the topographic effects (e.g. Ulusoy et al., 2012) or by comparing the observations to results of land surface models (e.g. Romaguera et al., 2018).

Acquiring airborne or drone-borne TIR imagery with smaller pixel sizes is one solution. The smaller pixels give a more representative pixel-integrated temperature for the anomalies and increase the contrast between the true anomalies and the surrounding background temperatures. Furthermore, smaller pixels allow detection of surface manifestations that are in smaller clearings of otherwise vegetated areas (e.g. intra canopy areas).

For regional, spaceborne acquisitions, a possible solution is a new sensor called ECOSTRESS (Hulley et al., 2017). ECOSTRESS data is processed to a 70m pixel size, which makes it the highest spatial resolution imager for regional surface temperature mapping. It is currently mounted on the International Space Station and follows its precessing orbit. This orbit results in different overpass times, which allow a) to acquire images at the optimal time of pre-dawn and b) allow to look at time series of nighttime temperatures to better model and remove disturbing thermal inertial effects of material properties, such as albedo, density and heat capacity on the detection results. It also allows to model the temperature decay rate during the night and the expected stable end temperature at the end of the decay, which should be largly free of the solar heating effects of the day and give a much better separation of true geothermal hotspots from false anomalies. In summary, ECOSTRESS can be used as test bed to optimize regional geothermal temperature anomaly detection from a spaceborne platform.

6. CONCLUSIONS

In this paper, we look at some of the factors that influence the detection of these geothermal surface temperature anomalies. Bias in the surface temperature measurements may increase the expected anomalous temperatures of these surface expressions. Vegetation cover and atmospheric gases can also partially block the radiated energy from the surface manifestation and reduce its recorded temperature contrast with the surrounding areas. Solar heating and materials with high heat capacity (solid rocks; soils with high moisture content; vegetation) show increase temperature due to solar forcing (i.e. sunshine) which may be misclassified as fals positive geothermal anomalies. ECOSTRESS with 70m pixel size and a satellite orbit that allows different overpass times may be able to help reduce some of these influences and look at the temperature decay rates in time series through the night rather than temperature images at a single moment in time. These issues need to be understood and tackled in order to maximize the usability of TIR satellite data in mapping of geothermal anomalies.

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