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A REVIEW OF GEOTHERMAL MAPPING TECHNIQUES USING REMOTELY SENSED DATA

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ABSTRACT
Exploiting geothermal (GT) resources requires first and foremost locating suitable areas for its development. Remote sensing offers a synoptic capability of covering large areas in real time and can cost effectively explore prospective geothermal sites not easily detectable using conventional survey methods, thus can aid in the prefeasibility stages of geothermal exploration. In this paper, we evaluate the techniques and approaches used in literature for the detection of prospective geothermal sites. Observations have indicated that, while thermal temperature anomalies detection have been applicable in areas of magmatic episodes and volcanic activity, poor resolution especially from space borne data is still a challenge. Consequently, thermal anomalies have been detected with some degree of success using airborne data, however, this is mostly in locations of known surface manifestations such as hot springs and fumaroles. The indirect identification of indicator minerals related to geothermal systems have been applied using multispectral and hyperspectral data in many studies. However, the effectiveness of the techniques relies on the sophistication and innovative digital image processing methods employed to sieve out relevant spectral information. The use of algorithms to estimate land surface temperature and heat fluxes are also applied to aid thermal anomaly detection, nevertheless, remote sensing techniques are still complementary to geologic, geophysical and geochemical survey methods. While not the first of its kind, this review is aimed at identifying new developments, with a focus on the trends and limitations intrinsic to the techniques and a look at current gaps and prospects for the future.

Keywords: Geothermal, remote sensing, thermal anomalies, indicator minerals, multispectral, hyperspectral

INTRODUCTION

Globally, there is a serious energy concern as a result of fossil fuels combustion which causes climate change. The exhaustibility of such fuels, their unreliability, and environmental implications have resulted in the search for alternative sources of energy. Geothermal energy, which is the energy of the 'Earths Heat', offers a renewable and reliable source of energy. However, as with most renewable energies, it is inherently regional and site specific, mostly associated with areas of magmatic episodes and crustal plate movements.

GT systems usually occur in areas of crustal heat and surface expressions which are classified as high or low temperature systems. High-temperature systems are defined as systems in which the temperature at 1 km depth is beyond 200°C and low-temperature systems are those in which the temperature is below 150°C in the uppermost kilometer (Huenges and Ledru, 2011). Hydrothermal systems forms where water of meteoric origin seeps into the ground through tectonic faults, and comes into contact with a heat source such as a magma. Through convection, such waters can be transferred back to the surface resulting in the formation of surface manifestations including; geysers, hot springs and fumaroles (Heasler *et al*., 2009).

In areas where the heat contained within hot dry rocks, faults and permeable strata is sufficiently reachable, it can be harnessed for geothermal power generation through the injection of water into the reservoir which becomes superheated and rises as steam through a production pipe. The steam is used to turn the turbines which generate electricity. In areas where the heat is low, such systems are suitable for direct GT exploitation including; greenhouses, home heating, aquaculture, industrial, tourism and recreational uses. Fig. 1 illustrates a model of the dynamics in a geothermal system.

Renewable energies are regional in nature, thus while solar and wind energy could be harnessed effectively in sunny and windy areas, GT energy have been associated with areas of crustal manifestations and tectonic plate boundaries. Estimation of the potentials of GT energy resources requires information on their location, depth, temperature and surface manifestations such as hot springs, fumaroles, geysers and associated minerals.

Several remote sensing methods have been employed in case studies previously for direct or indirect mapping and exploration of GT potential areas. This paper is aimed at identifying the role of remote sensing applications in GT area detection, mapping and exploration as complementary techniques to other geological methods. Although there have been earlier reviews on GT detection and exploration by Prakash (2012) and van der Meer *et al*. (2014). The earlier reviews needed to be complemented by identifying the new trends, approaches and techniques that have developed since then in the related field. This review is intended to supplement those new developments. The objective of this paper however, is to highlight the challenges and limitations inherent in the techniques while examining the successes and gaps in literature, with a view to understanding the future prospects and the way forward.

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Mapping Geothermal Anomalies Using Thermal Infrared Remote Sensing (TIRS)

In the most recent couple of decades, remote sensing has reached from an exploratory to an operational level. The expansion in the number of earth observation satellites, the progression in tools and handling procedures, innovative digital processing techniques and the utilization of data for new applications has been phenomenal (Prakash, 2000). Thermal infrared sensing, a branch of remote sensing concerned with the sensing of 'Emissions' from the object of interest rather than the 'Reflections' as in Optical or 'Backscatter' in Radar remote sensing, offers a unique set of data especially suited for detection of GT areas. Consequently, several studies have used thermal infrared data for GT studies (Coolbaugh *et al*., 2007; Haselwimmer *et al*., 2013; Hellman and Ramsey, 2004; Mia and Fujimitsu, 2013; Mia *et al*., 2014; Qin *et al*., 2011; Vaughan *et al*., 2012). GT areas have characteristic features such as fumaroles, geysers, hot springs. These features emit heat detectable to thermal infrared sensors onboard various airborne or space borne platforms, which are used to map and quantify temperature anomalies and heat flux synoptically from prospective areas. This can serve as target clue for later ground based surveys.

Airborne Thermal Data Applications

Studies by (Dean et al., 1982; Hochstein and Dickinson, 1970; Hodder, 1970) provided some pioneering remote sensing applications to GT exploration and detection of temperature anomalies. Hodder (1970) established the feasibility of performing initial reconnaissance survey of an unmapped area using airborne sensors around geothermal regions in Long Valley and Salton Sea,

California. The study used multiband photography in the visible and near infrared portions of the Electromagnetic Spectrum (EMS) to delineate anomalous spectral reflectance associated with hydrothermal alteration zones. Passive infrared imagery in the 8um to 14 um bands and 16 GHz and 19 GHz microwave bands were used to detect combined temperature and emissivity anomalies. Ground based surveys using thermometric and geophysical methods were used for verification. In spite of the coarse and poor resolution of the image data used due to the technology at the time, the study provided the basis for GT area detection and exploration in unmapped areas using remote sensing methods.

Dean, *et al*. (1982) used an x-band (2.4 -3.8cm) Radar and (10um -12um) thermal emissivity data to study the thermal anomalies and structural elements at the Pilgrims Hot springs in Alaska. The Radar horizontal (HH) and vertical (HV) dual polarized imagery were used to detect lineaments which indicated possible fractures as conduits for rising hot springs. The Thermal data was employed to detect radiant surface temperature and anomalies for GT heat sources using the density slicing technique. The study indicated the capability of high altitude Radar and airborne thermal imagery to provide useful data on structural setting and distribution of GT anomalies in site specific studies. However, it highlighted the initial shortcomings in the incapability of thermal imageries to really distinguish GT anomalies and other non-geothermal responses at a regional scale thereby suggesting the applicability of high altitude pre-dawn thermal imagery for detecting large areas in especially site specific studies.

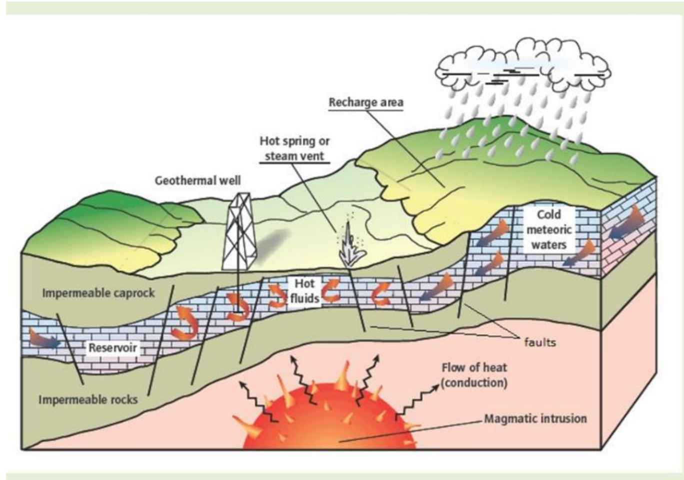

Fig. 1: Schematic representation of a typical Geothermal system, modified from (Bertani, 2010)

The use of digital image processing and better image resolution data could have addressed such limitations. Other early studies carried out (Dawson and Dickinson, 1970; Friedman, 1972; Pálmason *et al*., 1970) were more concerned about describing the possibility of airborne remote sensing application in detecting GT activity on thermal infrared (TIR) data, rather than detailed processing and analysis of the data. Numerous studies have used airborne remotely sensed data to quantify radiant heat flux and thermally anomalous areas as inputs to aid detecting GT potential areas, however, most of these studies are carried out in tectonically active and volcanic regions (Allis *et al*., 1999; Bromley *et al*., 2011; Haselwimmer, *et al*., 2013; Mia and Fujimitsu, 2013; Mia, *et al*., 2014; Vaughan *et al*., 2010; Vaughan, *et al*., 2012; Wu *et al*., 2012)

Allis, *et al*. (1999) examined a predawn airborne thermal data over the Dixie Valley and Wairakei GT fields in Nevada, USA and New Zealand respectively. The study mapped the near surface Geothermal Heat Flux (GHF) using on-site shallow temperature measurements and a predetermined soil heat conductivity (~0.5 W/m°C). The study demonstrated an empirical link between surface conductive heat flow and thermal infrared surface temperature values in areas of heated ground.

Bromley, *et al*. (2011) used airborne thermal imagery to calculate the heat flux associated with steaming ground at the Wairakei-Tauhara GT system in New Zealand by applying three practical methods to establish empirical relationships at a number of steam heated sites including estimation of; surface temperature, boiling point depth and total surface heat loss. Bromley, *et al*. (2011) developed consistent values for heat flux related to steam heated ground of 35.6, 33.4, and 32.4 MWth respectively for the three different methods. The study has implication in enhancing the predictive capabilities of future GT reservoir monitoring and simulations.

Haselwimmer, *et al*. (2013) quantified the heat flux and out flow rate of hot springs using an airborne broad band forward looking infrared radiometer- FLIR acquired thermal imagery (1m pixel size) in the Pilgrims Hot Springs, Alaska. The study demonstrated the potential of using airborne TIR imagery acquired with a FLIR camera (7.5-13 um) to quantify the heat flux in GT systems and the applicability of detecting GT heat flux (GHF) at lower altitude of about 1000m and 750m AGL for higher resolution, especially for systems having low temperature which could not be detectable at higher space borne altitudes. The study identified a rapid and repeatable method for quantitative investigations of spring-dominated systems which can support GT resource assessment, and long-term monitoring.

Recently, Neale *et al*. (2016), used airborne thermal infrared (8-12 um) data acquired using a FLIR SC640 TIR Camera for mapping and monitoring temperature anomalies around the Hot springs and Norris Geyser Basins in Yellowstone National Park, USA. The study identified fracture related hydrothermal changes around studied hydrothermal features caused by permeability and changes related to ground deformation. Results of the study still indicated limitations such as residual solar heating in temperature maps which further demonstrates the need for improved methods to quantify radiative surface temperature from airborne imagery.

Spaceborne Thermal Data Applications

Over the years and particularly in recent studies, the launch of space borne platforms such as Landsat satellites (most recent Landsat 8 with thermal bands 10 &11), Terra and Aqua, coupled with better sensors such as; Operational Land Imager (OLI), Thermal Infrared Sensor (TIRS), Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS), have drastically improved data quality and availability. This resulted in an increase in GT exploration and detection studies (Calvin *et al*., 2015; Coolbaugh, *et al*., 2007; Eneva *et al*., 2006; Fitts, 2013; Hanson *et al*., 2014; Haselwimmer, *et al*., 2013; Heasler, *et al*., 2009; Kratt *et al*., 2010; Mia, *et al*., 2014; Nishar *et al*., 2016; Prakash, 2012; Qin, *et al*., 2011; Reath and Ramsey, 2013; Vaughan, *et al*., 2012). Consequently, a number of previous studies in literature have used data from–ASTER, and LANDSAT thermal data.

Coolbaugh *et al*. (2000) used a combination of thermal infrared multispectral scanner (TIMS) band 5 - night time, and advanced visible and infrared imaging spectrometer (AVIRIS) data to investigate thermal patterns and GT anomalies at Steamboat Springs, Nevada. The study employed two techniques on the TIMS and AVIRIS data to enhance GT anomaly by subtracting the effects of topography, albedo and thermal inertia. The study highlighted the limitations posed by high albedo and thermal inertia resulting in the difficulty in detecting thermal anomalous features in pre-dawn thermal images.

Eneva, *et al*. (2006) analyzed space borne TIR ASTER imagery for detection of thermal anomalies associated with surface GT manifestations in Central East California. The study compared corrected & uncorrected night time ASTER –AST_08 (surface temperature) by evaluating the thermal effects caused by topography and albedo in the Coso GT project area. The results indicated the applicability of a simplified model which is potentially effective in enhancing thermal anomalies associated with GT manifestations, while suppressing 'false' anomalies. Although not supported by field validations, the study was another initial attempt at GT area detection using satellite thermal data.

Coolbaugh, *et al*. (2007) investigated the ability of ASTER images to detect surface temperature anomalies associated with GT activity at the Brady's Hot springs, Nevada. In the study, ASTER visible and near infrared - VNIR data were processed iteratively to highlight subsurface contributions of GT heat and to minimize the effect of temperature variations resulting from diurnal heating effects of the sun. The study identified the possibility of reducing background temperature without decreasing the intensity of GT anomalies making it easier to discriminate GT expressions from 'false' anomalies on images caused by non-thermal springs, topographic effects and in the proportions of soil, rock & vegetation.

Qin, *et al*. (2011) used a Landsat ETM+ TIR to detect GT anomalies in the Tengchong area of China. The study employed the single channel algorithm to retrieve land surface temperature (LST) due to the single thermal band of the Landsat data. Four GT areas were detected based on geothermal mechanistic analysis and regional geologic investigation which demonstrated a correlation between the distributions of GT areas with development of fault structures. Despite highlighting the surficial limitations of remote sensing, the study indicated the applicability of thermal anomaly detection for GT exploration using LST retrieval.

Vaughan, *et al*. (2012) investigated ASTER and MODIS thermal data for Yellowstone National Park obtained in the 2000 to 2010 period for detecting surface geothermal anomalies and radiant heat flux of GT zones. The study distinguished normal background thermal changes in order to perceive and identify strange changes in GT activity. Vaughan, *et al*. (2012) indicated the possibility of overcoming the difficulties of directly measuring Geothermal Heat Flux especially over wider geographical areas using the synoptic capabilities of remote sensing. The study demonstrated how the component of TIR can be monitored over large areas simultaneously and frequently with sensitivity to subtle changes associated with; tectonic, volcanic, and hydrothermal for GT monitoring applications using MODIS and ASTER TIR data.

Mia *et al.* (2014) used a Landsat ETM+ image data for thermal activity exploration at Aso volcanic area in Japan. The study employed three approaches including; hydrothermal alteration mapping of GT indicator minerals, LST estimation using the mono-window algorithm and radiance heat flux (RHF) quantified using the Stefan-Boltzmann's equations to identify thermally anomalous regions. The study results indicated a spatial distribution of spectral emissivity range from 0.94 to 0.99 and a LST map which conforms to the hydrothermal alteration mineral results and shows highest values in 2008 and lowest in 2011. The results of RGH showed highest pixels as 296 W/m2 with the highest heat discharge rate (HDR) of 3918MW and lowest as 2289MW.

Lashin and Al Arifi (2014) conducted a GT energy potential assessment at Al-Khouba in Southwestern Saudi Arabia, using Landsat 5 & 7 data, geothermometric analysis and 2D electric survey to estimate the reservoir potential of several hot springs in the study area. The study revealed the presence of good GT anomalies characterized by good petro-thermal properties with high temperature of about 78^{o}C. Estimated thermal properties were found to be 144 mW/m^{2} heat flow, 318kj/kg discharge enthalpy and a subsurface temperature of 133^{o}C. Consequently the results shows that the reservoir had a good GT potential of 17.847MWt.

Tian *et al.* (2015) combined Landsat 8 OLI & TIRS data with spectral range visible (0.435 um -0.445um) to TIR (10.60um - 11.19um), a 3D sub-surface temperature (SST) and LST measurements to assess the GT resource potential in Hokkaido Island, Japan. The study indicated the cost effectiveness of using TIR data for regional detection of GT resources especially with ground based data such as borehole logging temperature (BHT) at depths. The study used 28,476 well logging temperature from 433 sites. LST were retrieved using the Planck's inverse equation. Models such as Kriging with External Drift (KED) together with geo-statistical methods indicated the robustness of integrating satellite data and ground based techniques for reliable detection of GT anomalies and GT resources. However, the size of the well logging temperature data points and sites made such method difficult for replication especially in areas where data could hardly be available.

Mapping Associated Alteration Minerals as Proxy for Geothermal Exploration

Several previous studies have employed both Hyperspectral and multispectral data to identify spectral signatures of indicator minerals associated with GT reservoirs for indirect detection of geothermal areas (Calvin, *et al*., 2015; Hanson, *et al*., 2014; Hellman and Ramsey, 2004; Kratt *et al*., 2006a; Kratt, *et al*., 2010; Reath and Ramsey, 2013; Vaughan *et al*., 2003; Vaughan *et al*., 2005).

Mineral mapping using Hyperspectral data

The Hyperspectral remote sensing involves image acquisition in several narrow contiguous spectral bands resulting in the construction of full spectrum that can be related directly to field or laboratory spectra (Van der Meer and De Jong, 2011). It offers the advantage of providing hundreds of spectral bands which allows for imitating of radiance spectra obtained from the field and compared with field data. Hyperspectral data can be used in many applications including mineral detection.

Hyperspectral imagers aboard modern satellites and airborne platforms are capable of discriminating among the different spectral signatures of different minerals for indirect assessment of prospective GT areas. Observable changes from hydrothermal systems within GT prospective sites can produce changes in plants, soil and minerals detectable to hyperspectral imagers (Kratt, *et al*., 2010). The Hyperion, a hyperspectral space borne imager has been operational since the year 2000 and provides a high resolution data capable of resolving 220 spectral bands in the visible and shortwave infrared (VNIR & SWIR) (from 0.4 to 2.5 μm) with a 30-meter resolution. The instrument has a footprint of 7.5 km by 100 km land area per image, and gives detailed spectral mapping in 220 channels with high radiometric accuracy (Kratt, *et al*., 2010).

Martini *et al.* (2003), elucidated the usefulness of the Hymap hyperspectral mineral mapping in support of GT exploration in the Dixie valley, Nevada and Long valley, California. The study showed how airborne hyperspectral imaging provides hydrothermal mineral distribution maps synoptically. The study indicated that hyperspectral based mineral mapping in GT environments can provide an analysis of hydrothermal flow paths, discharge points, chemistry and structure.

Vaughan, *et al*. (2003) made several contributions in exploration of geothermal areas by proxy using identification of mineral indicators associated with GT areas. The study explored the new Hyperspectral thermal sensor; Spatially Enhanced Broadband Array Spectrograph System (SEBASS) in mapping surface minerals at Steamboat Springs, Nevada. The ability of SEBASS in measuring radiance in 128 contiguous spectral channels in the 7.5um to 13.5 um with a spatial resolution of 2m made it possible to create mineral maps with a pixel classification routine based on matching instrument and laboratory measured emissivity spectra. Minerals that are uniquely unmapped using VNIR & SWIR data e.g. quartz, feldspar and chalcedony were identified by SEBASS. The study noted, that despite the need for improvements in hyperspectral instruments and information extraction, the hyperspectral thermal data still shows a marked improvement over multispectral TIR imagery by its ability to map surface and lithology units with subtle difference in mineralogy.

In a subsequent study, Vaughan, *et al*. (2005) evaluated airborne MODIS/ASTER (MASTER) simulator and Hyperspectral (SEBASS) TIR image data for mapping surface mineral characteristics of active GT systems at Steamboat Springs, Nevada. The MASTER data was used to map the extent of the active GT areas indicated by silica-rich & clay-rich areas. The SEBASS was used to map same areas in addition to identifying minerals such as; opal, quartz, alunite, amorthite albite and kaolinite. Vaughan, *et al*. (2005) observed that opaline sinter are the most diagnostic expressions of hot springs activity, thus serve as primary indicators of recent geyser activity. While chalcedony are characterized with ancient sinter deposits and anhydrous sulfate minerals indicate locations of fumarole activity. The study represents an initial attempt at comparing Multispectral and Hyperspectral data as well as remotely sensed and field derived data focused on identifying important minerals associated with GT exploration.

Nash *et al*. (2004), used the advanced visible and infrared imaging spectrometer (AVIRIS) hyperspectral data to analyze and map soil mineral anomalies related to past and present GT systems as a tool for exploration in the Dixie valley, Nevada. The study employed supervised and unsupervised spectral unmixing methods to sieve out mineral endmembers and detected anomalous soil minerals related to GT systems and lithological structures. The study indicated how soil mineral anomalies may result from hydrothermal altered regolith due to fluids circulation within faults, fumarolic activity and extinct surface manifestations could be useful in locating blind GT systems and aid GT exploration.

Kratt, *et al*. (2006a) explored the use of HYMAP (Hyperspectral Mapper) airborne scanner system that measures radiance in the 0.45–2.5 μm range to remotely identify specific GT indicator minerals at Brady's Desert Peak, Nevada GT area. Minerals such as sinter, tufa, and sulfates manifested diagnostic characteristics in the VNIR and SWIR spectrum, consequently their presence and location could aid a more in-depth GT exploration. The study indicated that surface manifestations of gypsum, $CaCO_3$, hematite and opaline silica were identified together at the sites using hyperspectral data, which is indicative of GT activity at the location. The study shows the applicability of HYMAP data for GT exploration in especially areas that lack obvious thermal anomalies.

Reath and Ramsey (2013) employed a Hyperspectral SEBASS data to understand the mineral characteristics and thermal distribution of active GT systems of the Salton Sea, California GT fields. The high spatial resolution 1m SEBASS data and its 128 narrow channels allowed the identification of rare mineral assemblages associated to active GT areas. Specific GT indicator minerals identified include anhydrite and a rare Mg-sulfate with unknown hydrate state. The proximity of these minerals to the active GT areas indicates their relation to GT processes (Reath and Ramsey, 2013). The study indicates the accuracy of TIR

remote sensing for active GT exploration focusing on spectral emissivity mapping instead of detection of thermally anomalous pixels. Space borne sensors like ASTER TIR channels are more suited for global mapping of general mineral groups while SEBASS airborne sensor and the Mineral and Gas Identifier (MAGI) offer much better spectral and spatial resolution for mapping, detection and quantifying minerals associated with GT areas.
Littlefield and Calvin (2014) used a combination of 3 airborne imaging spectrometer instruments including; AVIRIS, HYMAP and ProSpecTIR to identify new prospective GT systems in Fish Lake Valley, Nevada. The study demonstrated the potential for using VNIR to SWIR (0.4 – 2.5 um) data, for mapping surface mineralogy to aid the identification of new GT areas in poorly explored regions. The results discovered additional GT resources as targets for future exploration including; two areas of sinter and travertine deposits, crystalline travertine and argillic alteration zones within fault ranges. The study employed an innovative decorrelation stretch technique suitable for GT prospecting.

Recently, Calvin and Pace (2016), demonstrated the value of the proposed Hyperspectral Infrared Imager (HyspIRI) instrument in Southern California. The study focused on mapping several geologic phenomena including; fumarole fields, sand dunes, hydrothermal alteration, lithology and thermal anomalies. The results illustrated a promising applicability of the HyspIRI remote sensing instrument for GT mapping and mineral exploration in the future.

Mineral mapping using Multispectral data

In recent years, the Advanced Space borne Thermal Emission and Reflection Radiometer – ASTER, on the Terra platform launched on December 18, 1999 has provided enhanced mineral mapping capabilities for the geologic remote sensing community. However, unlike hyperspectral imagers which have hundreds of narrow contiguous bands, the multispectral imagers such as ASTER has 3 bands in VNIR, 6 bands in SWIR and 5 TIR with 15m, 30m and 90m spatial resolution respectively (Van der Meer *et al*., 2012). ASTER is without a band in the blue wavelength which Landsat has, thus cannot produce natural colour composites. However, the bands in SWIR enables a wealth of mineral indices to be calculated. Observation from previous studies on mapping of minerals associated with GT areas have indicated that studies mostly employ a combination of multispectral and hyperspectral data or with other field spectroradiometer.

Kruse (2002) used a combination of Multispectral short-wave-infrared (SWIR) and long-wave-infrared (LWIR) data to map minerals related to hot springs and epithermal mineral deposits. Active and inactive hot springs and deposit types were studied using the MODIS/ASTER airborne simulator (MASTER) and ASTER. The MASTER and ASTER data analysis contributed to mineral mapping in the VNIR/SWIR, consequently improving the mapping of siliceous sinter using LWIR signatures and the Integration of VNIR/SWIR/LWIR remotely sensed data in subsequent studies.

Kratt *et al*. (2006b) also used ASTER data and ASD- field spectrometer to map borates related minerals for indirect GT exploration in the playas of western Nevada. The study demonstrated that GT areas are sometimes characterized with fluids associated with surface crusts of borate evaporite minerals. In such environments, the borates can thus serve as an exploration tool provided it can be efficiently and effectively mapped in the field. The ASTER imagery reflectance characteristics of tincalconite 0.4-2.5 um region was used to remotely generate mineral abundance map for the area studied while ASD spectrometer field observations validated the presence of borate evaporates. Geochemical and geothermometer analysis suggested possible presence of hidden GT reservoirs.

Kratt, *et al*. (2010) used a combination of space borne multispectral ASTER data (VNIR, 0.5-0.8 um) and (SWIR, 1.6-2.4 um) with airborne Hyperspectral data (127 channels, 0.45-2.5 um spectral range) for an early GT exploration stage in the Pyramid Lake, Nevada. The ASTER was employed to provide an initial surface cover and thematic maps. The study identified minerals, including alunite, kaolinite, montmorillonite/illite, halloysite, carbonate rocks and gypsum using the hyperspectral data. The study noted that GT indicator minerals help to explore structural controls and orientation found in close relation with thermal springs, it aided a detailed detection of areas having the most GT potential and provided instances of how altered rocks and certain chemical precipitate can be used as GT exploration guides and the need to pay attention to such features which may appear subtle in the field.

Calvin, *et al*. (2015) used a combination of space borne and airborne instruments to identify minerals and thermal characteristics of surface indicators of GT resources in Nevada. Field spectral validation were done using ASD portable spectroradiometer (0.4-2.5 um). The study synthesized a series of minerals associated with GT activity including sinter, tufa, travertine, argillic, hydrothermal alteration minerals and evaporites. Calvin, *et al*. (2015) specifically demonstrated the effectiveness of a 2m depth temperature survey method developed by Sladek *et al*. (2009), in identifying small near surface thermal anomalies rather than remote sensing studies and recommended a concurrent use of the method together with remote sensing for rapid, inexpensive surveys.

Calvin, *et al*. (2015) also summarized a number of minerals specifically associated with geothermal locations. These include; Clay such as Kaolinite, Illite, and Muscovite which are geothermally associated with argillic alteration of feldspar, argillic alteration of feldspar or muscovite and phyllic alteration of feldspar respectively. Sulfates including; Alunite and Gypsum geothemally related to advanced argillic alteration of potassium feldspar and evaporate deposition from sulfur-rich springs respectively. Carbonates including; calcite like travertine and tufa, which are deposited by sub-aerial and sub-lacustrine calcium-rich springs or in veins, respectively. Silica such as Opal or Chalcedony geothermally associated with amorphous silica gel which may fill fractures or are deposited as hot spring sinter and as sinter ages, which develops structural order similar to quartz. Borates such as Tincalconites geothermally related to Evaporites formed near borate-rich springs in playas (Calvin, *et al*., 2015). These minerals could thus serve as indicators of GT activity and can be used as proxy for identifying hidden GT systems which may be without obvious surface expressions.

Land Surface Temperature (LST) Retrieval for Detecting Temperature Anomalies in GT Prospecting

In GT exploration using remote sensing, surface thermal anomalies are used as indicators of possible GT resources. These anomalies are detectable using surface temperature maps produced from LST derived from images. The LST are retrieved from remotely sensed data. Several algorithms have been identified for LST retrieval (Du *et al*., 2015; Jin *et al*., 2015; Li *et al*., 2013; Rosenstein *et al*., 2014; Sobrino *et al*., 2004; Wang *et al*., 2015a; Wang *et al*., 2015b; Yu *et al*., 2014)

Theoretical basis of LST

In thermal remote sensing, the concern is on the 'Emissions' from the target. Thermal infrared sensors onboard remote sensing platforms usually measure 'Radiant Temperature' Prakash (2000). The Radiant temperature (T_k) being the actual temperature obtained in remote sensing, is a function of Kinetic temperature (i.e. the surface temperature of a body and the amount of heat contained in it) and the emissivity (i.e. the emitting ability of a material in relation to that of a black body) of the object or target of interest. The black body being an object theoretically able to absorb and then emit all energy incident upon it.

All objects with temperature greater than absolute zero (-273 Kelvin) emit radiation, and the amount of radiation from a black body in thermal equilibrium at wavelength λ(m) of electromagnetic waves and temperature T is described by Plank's law as:

$$B(\lambda, T) = \frac{c_1\lambda^{-1}}{\pi(\exp(c_{\frac{2)}{\lambda T}} - 1)}$$

Where B (λ,T) is the spectral radiance of the black body in units of Wm^2 μm^(-1) ⟦sr⟧^(-1), and in practice, it is the emitted radiance of ground object. λ is wavelength in meters, T is temperature in K, c1and c2 are the spectral constants with c1= 3.7418×10−16W m2 and c2= 1.4388×10−2m K. When the emitted radiance of ground object B (λ, T) is measured, generally by thermal sensor, the temperature T can be computed by inverting the Planck's radiance function as follows:

$$\boldsymbol{T} = \frac{C_2}{\lambda\, ln\left[(C\frac{1}{\pi\lambda^5} B(\lambda,T)+1\right]}$$

Where T is the brightness temperature, to compute the actual surface temperature, radiometric and atmospheric corrections are carried out in addition to using a temperature retrieval algorithm. Depending on the number of thermal bands on a sensor, the split window algorithm or the single channel algorithm is used, the latter is employed where the sensor has a single thermal band, while the former is used if the sensor has two or more thermal bands to robustly retrieve LST (Qin, *et al*., 2011).

A comprehensive summary of the various land surface temperature retrieval algorithms using satellite data is provided by (Li, *et al*., 2013). Some of the commonly used in GT anomaly detection include; the single channel algorithm which has the advantage of being simple and applicable where a sensor has a single thermal band, but has limitations of requiring prior knowledge of pixel emissivity of TIR band, accurate atmospheric profiles which may be uncertain thus affecting results, and the use of empirical relationships resulting in poor outcomes at high atmospheric water vapour contents (Qin *et al*., 2001). And the split window algorithm which is based on the assumption of different atmospheric absorption in adjacent TIR bands, it has the advantage of being simple, efficient and suitable for sensors with not less than two TIR bands and does not require accurate atmospheric profiles. It however, requires priori knowledge of pixel emissivity in each TIR band, many parameterization of coefficients and a degraded accuracy due to large viewing zenith angles (Sobrino, *et al*., 2004). A number of studies have employed LST anomaly detection to identify areas of possible GT resources on remotely sensed imageries (Mia *et al*., 2012; Mia*, et al*., 2014; Qin, *et al*., 2011; Tian, *et al*., 2015). The choice of which LST retrieval algorithm used in the studies have been influenced by the characteristic of the thermal sensor used to acquire the thermal data. Most previous studies that employed the Landsat 7 Enhanced Thematic Mapper plus - ETM+, which has single thermal band, have used the single channel algorithm (Qin, *et al*., 2011). While studies using multiple thermal bands have used the split window algorithm (Du, *et al*., 2015)

Qin, *et al*. (2011), detected the GT anomalous areas in Tengchong China, using the single channel algorithm to retrieve land surface temperature (LST) from a Land sat 7 ETM+ imagery. The study produced LST map which indicated areas of the lowest temperature as 281.3K and highest temperature as 295.84K. Four anomalous areas designated A, B, C, D were identified as having an overall statistics of 4-10K higher than the surrounding background temperature. The result was validated by comparison with a 1 KM MODIS LST which shows a temperature difference of within 1.3K for all the designated anomalous areas. The result was found to be consistent with Srivastava *et al*. (2009), that comparisons between MODIS & Landsat ETM+ has a maximum difference of 20C, making it acceptable for GT detection (Qin, *et al*., 2011)..

Tian, *et al*. (2015), modeled LST and subsurface temperature (SST) to detect temperature anomalous zones for GT area characterization using a combination of well logging database and a Landsat 8 band 10 thermal infrared imagery in Hokkaido, Japan. LST was estimated using the single channel algorithm. The study identified three (3) zones as highly potential for GT resources. The zones also correspond to fault zones and paths of hydrothermal flow & heat transfer. The study observed that 2 of the zones are located in areas of hot springs and volcanic activity, while another zone is in tectonically active region. Although the results may be affected by urban heat island (UHI), it indicates that modeling can practically and effectively evaluate GT potentials over a wide area.

There has been fewer studies on detection of anomalous temperature for GT characterization, most studies in literature usually estimate LST as an input to determining other variables such as radiative heat flux (RHF) and or geothermal heat flux (GHF)(Mia, *et al*., 2012; Mia and Fujimitsu, 2013; Mia, *et al*., 2014). Other studies quantify heat flux in tectonically active areas for monitoring volcanic activity and detecting possibility of eruptions.

Detection of Structural Faults and Fluid Paths for GT Characterization Using SAR Data

The application of remote sensing techniques especially the use of the VNIR-SWIR portions of EMS in GT detection has been constrained in tropical regions particularly due to obstacles imposed by vegetation cover. In such regions, there has been concerted efforts through the use of Radar remote sensing to overcome some of this limitation. A limited number of studies were undertaken to highlight the advantages and applicability provided by Synthetic Aperture Radar (SAR) systems due to its operability in all weather and day or night. Most studies however, focused on the use of SAR data to identify surface deformation, structure, faults as conduits to aid in identifying and characterizing GT systems.

Saepuloh. *et al*. (2012), used a combination of techniques to detect spatially, surface expressions of GT systems in the tropical Bacan Island, Indonesia. The study indicated the effectiveness of microwave sensing by its operational capability for surface observations regardless of weather conditions. The study used the fuzzy logic method and shows that, while Landsat TM VNIR data and ASTER TIR data provided details on the mineralogy and thermal anomalies, the ALOS/PALSAR microwave data highlighted geomorphologic and structural features and suggested an integration of the techniques for effective characterization of GT systems.

Saepuloh *et al*. (2015), evaluated the use of backscattering intensity of SAR data for detecting GT surface manifestations in torrid vegetated zones of Indonesia. The study attempted overcoming the limitations of cloud and thick vegetation in revealing surface geological features by employing an automatic extraction of Linear Feature Density (LFD) from SAR data to estimate fluid paths related to faults, fractures at mount Tangkuban, Java Indonesia. Polarimetric SAR data were used to identify the distribution of surface GT manifestations based on surface roughness. Fluid Path Index (FPI) and field investigations were used to confirm the location of the alteration zones in the SAR backscattering images. The study highlighted the usability of active remote sensing systems to complement and overcome some of the limitations of optical and thermal sensing by using microwave sensing which is operational in all weather and penetrates vegetation.

Ali *et al*. (2016), conducted a time series analysis to evaluate surface deformation as a consequence of GT exploitation at Brady's hot springs, Nevada. The study employed the Interferometric Synthetic Aperture Radar (InSAR) data to test the assumptions that GT production in exploited fields cause surface structural deformation. The study observed that mechanisms including thermal contraction of rocks, pores pressure reduction and mineral alterations over time combine to potentially cause structural deformation. The study indicated the significance of Radar remote sensing in structural detection for monitoring GT systems.

Recently, Maghsoudi *et al*. (2017) used a Persistent Scatter Interferometric Synthetic Aperture Radar (PS-InSAR) for detecting surface deformation in GT areas of West Java, Indonesia. The study compared the potentials of Sentinel 1A and ALOS PALSAR remote sensing data around Wayang Windu and Patuha GT fields. The results demonstrates the applicability and performance of available Sentinel 1A microwave data in mapping GT surface deformation in vegetated urban areas using PS-InSAR analysis.

There has been a limited application of SAR data in GT exploration. Most of the studies observed in literature focused on using SAR data for monitoring surface deformation due to GT fluid extraction and or exploitation within GT fields (Allis and Zhan, 2000; Carnec and Fabriol, 1999; Chang *et al*., 2005; Eneva *et al*., 2012; Eneva *et al*., 2011; Faulds *et al*., 2010; Fialko and Simons, 2000; Foxall and Vasco, 2008; Hole *et al*., 2007; Oppliger *et al*., 2004; Vasco *et al*., 2013).

Challenges and Limitations of GT Exploration Using Remote Sensing

In the pioneering stages of GT exploration using remote sensing, efforts were made towards detecting surface temperature anomalies. Although these initial studies ushered in the feasibility of such a technique in especially unmapped areas, the coarse and poor resolution of thermal data due to low level technology were the main challenges. Subsequent studies highlighted the inability of thermal imagery to really distinguish GT anomalies from 'false' GT responses particularly at regional scale using airborne thermal data (Dean, *et al*., 1982).

The advent of high resolution space borne thermal infrared data as a result of the launch of Landsat, Terra and Aqua satellite platforms coupled with thermal sensors TIRS, ASTER and MODIS, facilitated more studies in GT detection and exploration. Later studies (Coolbaugh, *et al*., 2007; Eneva, *et al*., 2006) thus attempted enhancing thermal anomalies for GT detection by suppressing 'false' anomalies using image correction techniques from high resolution ASTER and the correction of the thermal effects caused by topography and albedo. This limitation was expressed in the inability to use TIR sensing approach to model the diurnal heating effects of the sun as indicated in the study by (Coolbaugh, *et al*., 2000) where by a conventional pre-dawn thermal image was unable to detect a thermal anomaly at the main sinter terrace in Steamboat springs Nevada, despite the presence of several fumaroles in that location. This was as a result of the terrace having relatively high albedo which reflects much of the sun's energy during the day, it also has low thermal inertia caused by its high porosity, consequently cooling off quickly at night.

The usefulness of thermal infrared sensing of subtle temperature anomalies in GT exploration have also been limited due to the requirement for day and night time image pairs, predawn imagery and fairly extensive calibration to detect subtle temperature incursions. Consequently, surface thermal anomalies have only been detected in the immediate locations of obvious hot springs and fumaroles (Coolbaugh, *et al*., 2007). This is evidently shown by the recent work involving the use of FLIR imagery (Haselwimmer, *et al*., 2013) in which heat flux was quantified at known springs using airborne data. This further indicates the challenge in using satellite data, despites its availability, to detect subtle temperature anomalies due to poor spatial and spectral resolutions.

Recent studies by Qin, *et al*. (2011); (Tian, *et al*., 2015) have established the significance of TIRS techniques for GT exploration especially coupled with LST and SST methods. The studies, however, exposited the major limitations of remote sensing by its ability to detect the surficial thermal anomaly and sensitivity to only shallow GT resources and can only be used to infer on prospective GT areas. It is a complementary exploration step to in-depth ground based geological, geophysical and geochemical surveys.

Hyperspectral remote sensing which involves image acquisition in several, contiguous spectral bands resulting in the construction of full spectrum that can be related directly to field or laboratory spectra. This offered the advantage of having numerous narrower bands which as opposed to the few bands in multispectral data,

dramatically increases the precision of identification of minerals through unique spectral signatures. This has also been enhanced by hyperspectral signature library created in lab conditions containing hundreds of signatures for different minerals, land cover and earth materials. However, hyperspectral data has several limitations. The most significant is the engineering challenge to acquisition at sufficient quality especially at space borne level, this might explain why most of the studies noted in literature employ airborne hyperspectral data and even in cases where space borne data are used, it is mostly in combination with airborne data e.g. (Calvin, *et al*., 2015; Kratt, *et al*., 2010; Kruse, 2002; Vaughan, *et al*., 2005). Other limitations include complex calibration, pre and post processing of data, data redundancy due to acquisitions of many spectral regions of less user interest, environmental conditions and natural variations in materials, which makes them different from standard library materials, are still some of the many challenges in hyperspectral applications.
Satellite imaging usually covers a larger area at a lower cost than airborne hyperspectral surveys and is a good remote sensing option when surveying larger regions. However, airborne hyperspectral surveys despite being costly, typically produce greater spatial and spectral fidelity for imaging of surface indicators and are usually suitable in more site specific remote sensing operations. Consequently, majority of previous studies on GT exploration of surrogate minerals have employed airborne sensors e.g. SEBASS, Hymap due to higher resolution and better precision in mineral identification as compared to space borne sensors. The Hyperion, a hyperspectral space borne imager which has been operational since the year 2000 is not without its limitations, as a result of data quality, spatial coverage and the complexity of the pre-processing of the data.

Research Direction
There are a number of research questions needing critical evaluation and further research as regards mapping GT systems and remote sensing sensors in the foreseeable future. This is especially as new techniques and sensors such as the “HyspIRI” are expected onboard by the year 2020. These questions have been succinctly expounded by (Kruse, 2013):

As regards geothermal systems:
- “What are the magnitude of surface temperature at active hot springs and GT areas? How do temperatures vary naturally”? “What can surface temperature imply about the morphology and evolution of these systems and temperature at depths? How does surface temperature respond to GT exploitation”?
- “What can surface mineralogy tell us about the morphology and evolution of hydrothermal systems and the link between active GT systems and ore deposits”?
- “How are surface mineral assemblages of hydrothermal systems tied to underlying geologic constraints such as lithology, alteration, water chemistry and temperature regimes”?
- “What surface changes are taking place at active GT systems as a result of human activities such as recreation, GT energy exploration, and drilling and energy production”?

As regards to the proposed HyspIRI sensor
- “What would be the effect of the proposed HyspIRI spatial and spectral resolution on the detection, identification and characterization of key rocks, minerals, vegetation and other materials associated with active and fossil GT systems”?
- “What is the spatial scale of temperature features that can be detected using the proposed HyspIRI 60m spatial resolution”?
- “What is the temperature variation needed for detecting and identifying of GT systems at different scales”?
- “In measuring temperature at GT systems, what are the effects of spatial mixing and their nature and magnitude”?

Prospects for the Future
The availability of high resolution thermal imagery both spectrally and spatially could in the future, aid in the production of surface and sub-surface geothermal maps for reliable exploration and detection of GT resources. The availability and accessibility to remote sensing data as provided by the NASA USGS recently, could positively aid more research in GT detection and exploration. Advances recorded in the use of Unmanned Arial Vehicles (UAV), which are affordable, could lower the prohibitive costs of site specific surveys similar to airborne systems and aid studies using higher resolution data.
The synoptic capability of remote sensing systems especially space borne which covers large areas cost-effectively, establishes it as an attractive technique and a viable option especially at the prefeasibility stages of GT exploration which can also detect not only regional areas but also ‘blind systems’ not easily detectable using conventional survey methods. Improved and innovative digital processing techniques could enhance the detection of GT anomalies and exploration of prospective sites. Hyperspectral data provides advanced capabilities over multispectral VNIR and SWIR data for quantitative mapping of surrogate minerals such as; Clays, Silicates, Carbonates and other minerals associated with geothermal activity. This potentially increases the ability of mapping and characterizing blind geothermal systems and verifying other remote sensing investigations. Hyperspectral applications can be further supported by the proposed NASA HyspIRI in the future. The continuing research into the capabilities of the MAGI airborne sensor which could serve as a proto type for the HyspIRI could further enhance geothermal studies.

In the last few years, the progress recorded in terms of sensor, platform and digital processing technology has resulted in a transformation of Hyperspectral remote Sensing to Ultra Spectral Remote Sensing (USRS) (Staenz and Held, 2012). The successes of the Hyperion space borne hyperspectral sensor has prompted the plan for several hyperspectral satellite missions including; EnMAP, MSMI, HYPXIM, PRISMA, HISUI, HERO and HyspIRI from 2015 to 2018 (Staenz and Held, 2012). Technological
Advancements in the field of nanotechnology and microchips have facilitated the development of powerful hyperspectral sensors for UAV with superb spatial and spectral fidelity ranging from a few centimeters and 2-9 nanometers respectively (Tan, 2016). With such spatial and spectral resolutions, previously difficult to resolve spectral features using conventional hyperspectral imagers could be addressed. These revolutionary developments could also mean the need for additional computational requirements and improved digital image processing techniques to address more complex data.

The fusion of satellite hyperspectral and multispectral data in future studies could improve the precision of both data while overcoming the limitations inherent in individual sensing characteristics and resulting in higher spectral and spatial resolution. This could aid an effective discrimination of subtle anomalies from satellite data and improve GT exploration. The surficial detection of temperature anomalies is another limitation that hopefully could be overcome in the future when technologies that could penetrate deeper levels of the surface are invented hopefully through the Land sat Data Continuity Mission(LCDM).

Conclusion

Remote sensing offers a complementary input especially in the prefeasibility stages of GT exploration through the synoptic coverage of large areas and the detection of anomalies exhibited by surface manifestations and temperature. A majority of the studies noted in literature are those in the western United States of America (USA) and other proximate areas. Exploratory studies are especially carried out in the Yellow stone National Park. The sheer size of the park with an area of about 5000 sq. miles and thousands of surface manifestations such as hot springs, geysers, fumaroles (Heasler, *et al*., 2009), informs the need to employ remote sensing methods and techniques in exploratory monitoring of the area. Consequently, potential areas in the western USA have been the most geothermal exploited areas globally. Other areas include regions in Asia and Australia. However, relatively stable areas of the world like the African continent with subtle surface manifestations have not been adequately explored or exploited for GT resources, except in the recent Kenya region which happens to be in the east African rift valley tectonic subduction zone. The promising advances expected in Enhanced Geothermal Systems (EGS) could pave the way for other areas of the world to benefit from such limitless source of renewable energy. There is the need for more research in such uncharted regions for geothermal potential sites and their monitoring to which remote sensing systems and techniques can play a significant role. This could eventually serve the much needed power, or for recreational, tourism, heating, agricultural and other industrial purposes requiring less GT heat from the ground. Finally, this review observes that most previous studies on GT mapping were focused on areas with obvious manifestations, the challenge thus remains in advancing remote sensing sensor technology and improving techniques for mapping unconventional GT systems with subtle characteristics and which could hold substantial GT resources. This is important especially if GT resources are to competitively serve the needed renewable and sustainable alternative energy demands in the future.

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