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Review Paper

Prospecting for geothermal energy through satellite based thermal data: Review and the way forward

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ABSTRACT: Geothermal investors need to be confident with the methods and results of exploration programs. Also cutting the upfront cost of geothermal exploration will further encourage investors to consider investment in this emerging clean energy field. Hence, it is of paramount importance to improve prospecting techniques in order to explore where economic concentrations of geothermal energy are to be expected. The current study evaluates different approaches for downscaling thermal data from remote sensing images together with factors in surface and subsurface environment. The paper discusses case studies, the challenge and the way forward for geothermal prospecting as well as practical solutions to discrepancy that faces the mapping and documentation of spatial geothermal anomalies. It also discusses main criteria that should be considered while prospecting for geothermal energy.

Keywords: *Geothermal energy; Reflectance spectroscopy; Renewable energy; Satellite; Thermal data*

INTRODUCTION

Geothermal systems exist in regions of high crustal heat flux that may be associated with the occurrence of young igneous bodies or hot rocks located deeper in the crust (Rybach, 1981; Beadsmore and Cull, 2001; DiPippio, 2005; Blackwell *et al.*, 2006). This high geothermal heat is normally transferred to the surface by the convection of ground waters that forms hydrothermal systems. Fig. 1 shows conceptual geologic model of geothermal system where recharge results from meteoric groundwater driven by heat supplied from a buried magmatic system leading to a convective column. Steam separation results in fumaroles and steam adsorption by groundwater while hot springs occur associated with the formation of silica. Geothermal systems and associated geostuctures can be studied using remote sensing methods in order to save time and resources. Application of remote sensing technology to geothermal exploration have been discussed by Huntinghton, 1996; Kratt, 2005; Eneva *et al.*, 2006; Calving *et al.*, 2009; Bromley *et al.*, 2011. Principals and applications of indirect methods which involve using hydrothermal minerals as a proxy of geothermal systems were discussed by Hunt, 1977; Clark, 1999; Green *et al.*, 1998; Martini *et al.*, 2004 and Vaughan *et al.*, 2003 and 2005; whereas the direct thermal indices and associated applied methods were discussed in Mongillio, 1994, Hackwell *et al.*, 1996; Haselwimmer *et al.*, 2011; Rowan *et al.*, 2003; Coolbaugh *et al.*, 2007. Well-established methods in multispectral, hyperspectral analysis, in conjunction with modern subsurface geophysics, advanced imagery from space-based and airborne sensor systems, permits their direct and immediate application in geothermal energy prospecting and their evaluation using both thermal signature, and spectral signatures indices (Coolbaugh *et al.*, 2007; Gupta and Roy 2007). The present work demonstrates the opportunities and challenges of using direct and indirect remote sensing indices to map geothermal systems. However, the emphasis will be on thermal range data, which is considered direct method for geothermal heat flux

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estimates. Thermal data are essential in the decision making with respect to geothermal energy prospecting and planed geostructures. This article presents a discussion on the advantages and applications of thermal infrared (TIR) remote sensing to the delineation of surface temperature anomalies associated with geothermal activity, the measurement of near-surface heat fluxes associated with geothermal systems as input for monitoring and resource assessment, and mapping of surface mineral indicators of both active and recently active hydrothermal systems. A discussion on the spectral methods as an indirect mean to map features of geothermal systems will be presented based on highly cited original research on this field.

Bibliographical research indicated that there is a need to apply large-scale assessment methods to classify and prioritize zones of potential geothermal energy. Toward this end, remote sensing has a significant role. In the past four decades, remote sensing has been used for natural resource investigations which include geothermal prospecting. Image processing approaches have been used to identify and delineate earth target signatures using TIR emissivity data. Those approaches have not been used frequently due to data quality issues in terms of spatial and spectral resolutions, data correction issue among other limitations. Currently, the data quality has improved significantly. For example, multispectral instruments of ASTER/Landsat class have been most effective at broadly categorizing surface units that can be considered as proxy for geothermal systems (e.g., sulfates, carbonates, clays) than identifying specific minerals and their mixing components (Taranik, 1988, Sabine *et al.*, 1994, Rowan *et al.*, 2005 and Zhang *et al.*, 2007); whereas instruments of the MODIS class have been most effective at large-scale surface temperature mapping (Prata and Grant, 2001, Wright *et al.*, 2002 and Dean *et al.*, 2004).

Geothermal prospecting

Geothermal provenances with adequate heat flow to fuel power plants are found in rift zones, subduction zones and mantle plumes. The literature review (e.g. Clauser and Huenges, 1995; Gupta and Roy, 2007) indicated that an area may have a geothermal power deposition only if the following four main factors occur at the same place simultaneously: 1) a source of natural heat of great output, 2) an adequate water supply, 3) an aquifer or permeable reservoir, and 4) an impermeable cap rock. Worldwide, there are many localities with such properties listed above. A recent survey (Bertani, 2012) demonstrate that a total of twenty four countries

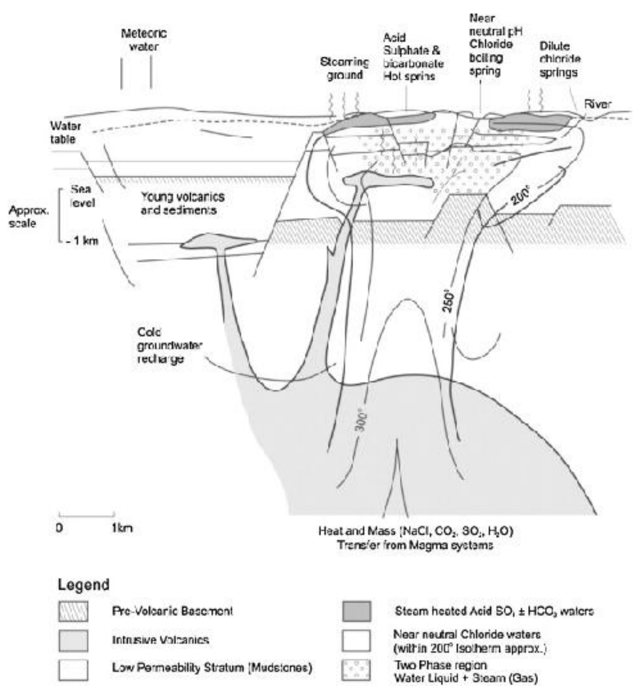

Fig. 1: Conceptual geologic model of geothermal system; modified after Henley and Ellis (1983).

now produce electricity from geothermal resources with a total installed capacity worldwide of 10,898 MW (corresponding to about 67,246 GWh of electricity). Germany, Papua – New Guinea, Australia, Turkey, Iceland, Portugal, New Zealand, Guatemala, Kenya, and Indonesia have increased the capacity of their power plant installations by more than 50% with respect to the year 2005. Successful remote sensing investigation for accurate prospecting and geostructure purposes should consider the following metrics: 1) the production of spatial surface and subsurface geothermal maps, 2) success of downscaling thermal airborne and satellite borne remote sensing data utilizing ground based measurements and analyses using numerical, statistical, and physical approaches, and 3) ability of hyperspectral data to identify minerals that have geothermal signatures.

Surface manifestations and fluids of geothermal systems

The surface manifestations of a geothermal system are usually the attributes that first stimulate exploration. Consequently, the identification, mapping, and evaluation of these attributes are important in the second phase or prefeasibility study, during which the geothermal potential is evaluated. The prefeasibility phase also include sampling fluids and gases to be investigated by hydrogeochemical method that assist in estimating the temperatures and the make up of hydrothermal reservoir fluids (DiPippio, 2005). Based upon the temperature and outflow rate of geothermal fluids, discrete surface features can include hot springs, seeps, fumaroles, geysers, mud-pots, and steam-heated pools. (Rybach, 1981; DiPippio, 2005).

The temperatures of geothermal fluids show a considerable range: low-temperature systems usually less than 90°C are referred to as spring-dominated as outflow occurs via hot springs or seeps. Systems with intermediate (90-150°C) and high (150-240°C) temperature fluids are vapor dominated as these fluids boil in the subsurface, due to lowering hydrostatic pressure, producing steam or water/steam dominated surface features (DiPippio, 2005; Gupta and Roy, 2007; Haselmmer and Prakash, 2012). However, the obvious feature of a geothermal reservoir develop when fluids leak to the surface along faults and fissures or through permeable rock units. Based on the reservoir temperatures and discharge rates, these surface manifestations take the form of seeps, fumaroles, hot springs, boiling springs, geysers, phreatic explosion craters, and zones of acid alteration. In addition, there are deposits of silica sinter, travertine, and/or the bedded breccias that surround phreatic craters (Henry, 1979; Rybach, 1981; Gupta and Roy, 2007; Haselmmer and Prakash, 2012).

Thermal-based remote sensing approaches

Thermal infrared remote sensing has previously been applied with varying success to investigate geothermal hot springs in many regions e.g. Alaska, Yellowstone and New Zealand. In Alaska, high-altitude (60,000 feet) thermal images had limited success in

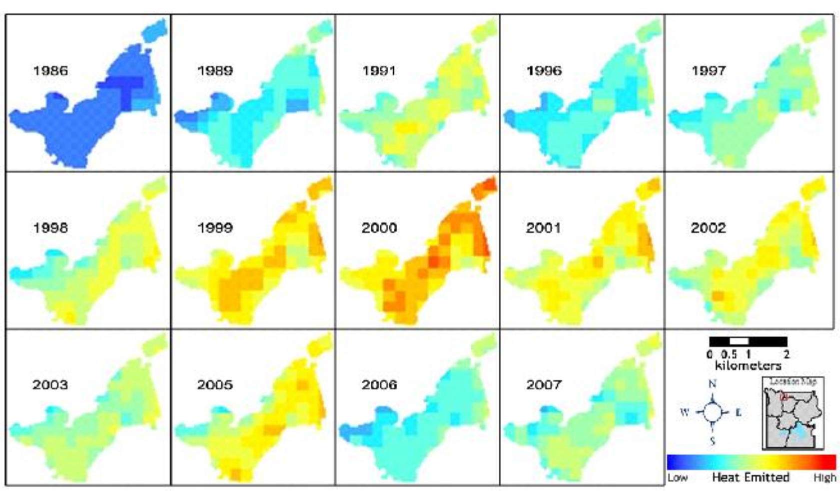

Fig. 2: Temporal variations of geothermal emittance data from the Mammoth Hot Springs area shows a general trend of increased emittance to 2000, and then decreased emittance from 2000 to 2007 (courtesy of NASA)

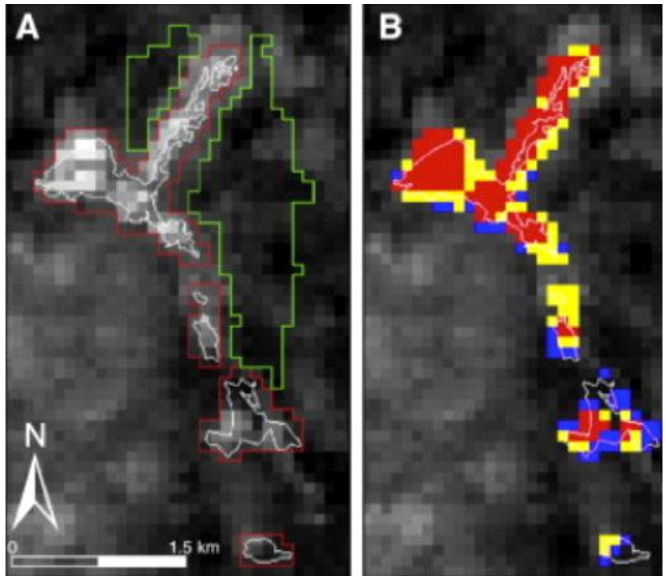

Fig. 3: ASTER images a) nighttime temperature at Heart Lake Geyser Basin thermal areas are outlined in white; the ASTER pixel areas encompassing the thermal area are outlined in red. Non-thermal background temperature pixels are outlined in green, B) The image shows how the thermal pixels vary from thermal background: blue pixels are average, yellow are two standard deviations greater, and red are four standard deviations greater. North is up; pixels are 90 meters resolution. (Courtesy R. G. Vaughan *et al.,* 2012, *Journal of Volcanology and Geothermal Research*)

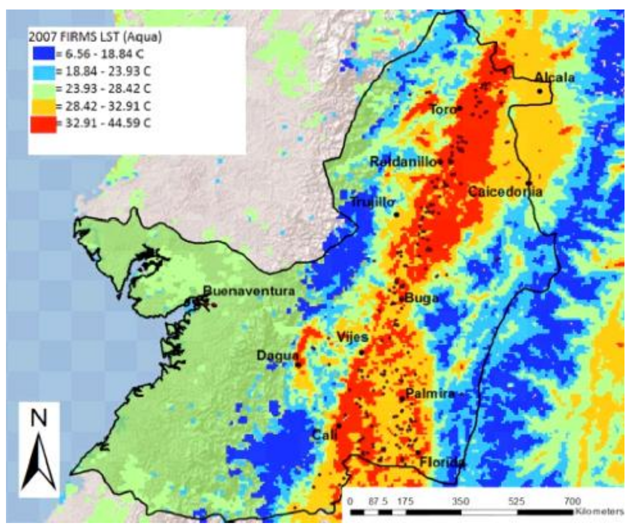

Fig. 4: Land Surface Temperature in Columbia derived from the Moderate Resolution Imaging Spectroradiometer – (MODIS) (data from SERVIR**,** which is a collaborative venture among the NASA Earth Science Division Applied Sciences Program, USAID, and worldwide partner institutions.

discriminating between warm ground and hot pools at Pilgrim Hot Springs that was due to the poor spatial and radiometric resolution of the thermal data (Dean *et al*. 1982). Dehn *et al*. (2006) employed airborne thermal imagery to study geothermal systems at Chena Hot Springs, Alaska and found a good agreement between radiative heat loss estimates calculated from the thermal data and shallow conductive heat loss obtained from shallow temperature and well data. Elsewhere, airborne thermal images have been applied to map

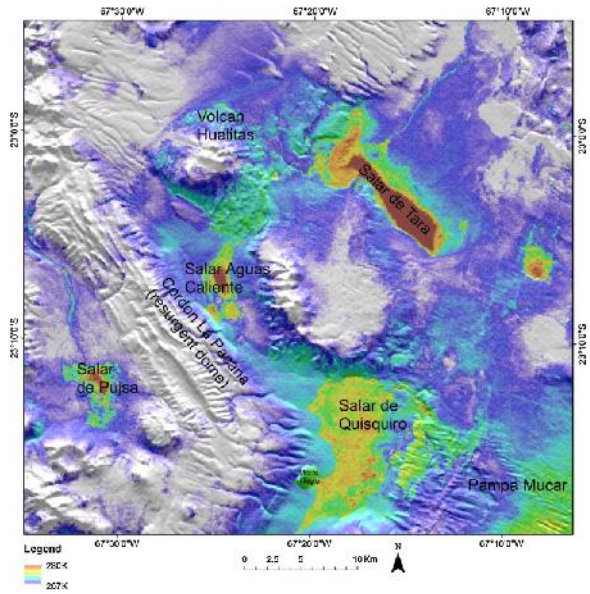

Fig. 5: Surface temperature map derived from ASTER nighttime imagery (after van deer Meer *et al.*, 2014)

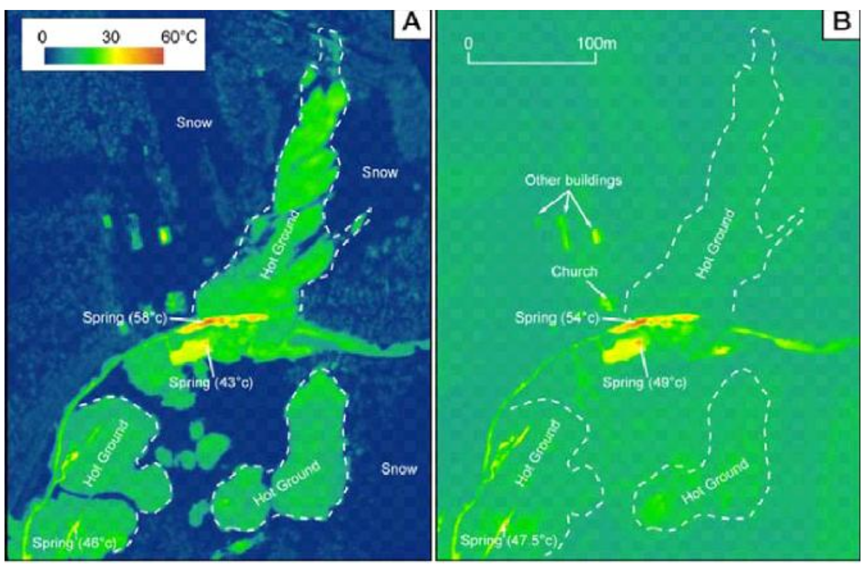

Fig. 6: Calibrated surface temperature data for part of Pilgrim Hot Springs acquired during winter 2011 (A) and fall 2010 (B) airborne surveys using a FLIR thermal camera. This data highlights the location of hot springs, hot pools and areas of heated ground as manifested in areas of anomalous snow melt in the winter2011 data; from Haselwimmer *et al.*, (2011) in Haselwimmer, and Prakash, 2012.

surface features and monitor the activity of the Yellowstone (Carr *et al.*, 2009; Jaworowski *et al.*, 2009; Haselwimmer and Parakash, 2012) geothermal system in the USA and the Waimangu-Waiotapu (Mongillo, 1994) and Taupo (Hodder, 1970) geothermal regions in New Zealand. Furthermore, thermal images have been used to directly quantify the heat flux from areas of geothermally heated ground (Bromley *et al.*, 2011; Carr *et al.*, 2009; Haselwimmer and Parakash, 2012; van deer Meera, *et al.*, 2014).

One of the satellites that have been used to map thermal activities is the Landsat satellites. Fig. 2 shows heat emittance as detected by Landsat images. The total energy picked up by the satellite images in Fig. 2 includes energy produced by the Earth itself, geothermal energy. Due to the fact that solar effects vary from year to year and with weather conditions, the average heat emitted from the surface of the investigated area for each year was subtracted from the total. The observed changes from year to year would then be primarily attributable to geothermal changes. In 1998, mineral-rich, near-boiling water bubbled in the study area, depositing calcite on the face of each terrace. This makes the detection and mapping activity a possible task.

Methods were also developed to monitor, in near-real time, the earth heat flux from infrared data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument and other sensors as well as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite (Hook *et al.*, 2001; Rowan *et al.*, 2003; Coolbaugh *et al.*, 2007; Baldridge *et al.*, 2009). Fig. 3 shows thermal areas versus non thermal areas as detected on ASTER pixels, and Fig. 4 shows surface temperature as detected on MODIS; whereas Fig. 5 shows thermal anomalies obtained from FLIR camera. Eneva *et al.*, (2006) applied a simplified version of the method used by Coolbaug *et al.* (2007) to map thermal anomalies in the Coso geothermal field, California, USA, also using a daytime/nighttime pair of ASTER images. Eneve *et al.*, (2006 simplified the correlation for thermal inertia effect due to the lack of field values of surface temperatures foe the 24 hour cycle; still the processed ASTER data was effective in enhancing some thermal anomalies and suppressing false positives. Whilst the method of Coolbaugh *et al.*, (2007) is effective at enhancing geothermal anomalies and suppressing many non-geothermal effects, there are several limitations of this approach. The method uses a simplified surface energy balance model that does not account for sensible and latent heat losses. The assumption of radiation being the main control on heat loss is valid for dry non-vegetated ground (Haselwimmer and Parakash, 2012). Van der Meer, 2014 reported other examples of the uses of surface temperature derived from TIR remote sensing data, including geothermal complexes in the Andes of Central Chile using ASTER data (Gutierrez *et al.*, 2012), where temperature map corrected for average back ground variations (Fig. 6) is demonstrated.

In another study, Haselwimmer *et al*. (2011) used 1 m spatial resolution airborne thermal imagery with a broadband FLIR systems A320 camera (operating in the 7.5 – 13 µm wavelength region) during fall and winter-time surveys over Pilgrim Hot Springs located near Nome in Western Alaska. The data was calibrated to surface temperature values using a combination of MODTRAN and an empirical adjustment with in-situ temperature measurements. The mosaicked and calibrated data enabled mapping of known and previously unmapped geothermal features including hot springs and pools, thermally anomalous ground (Fig. 7), and ice free-areas on the nearby Pilgrim River that indicated geothermal outflow at a distance from

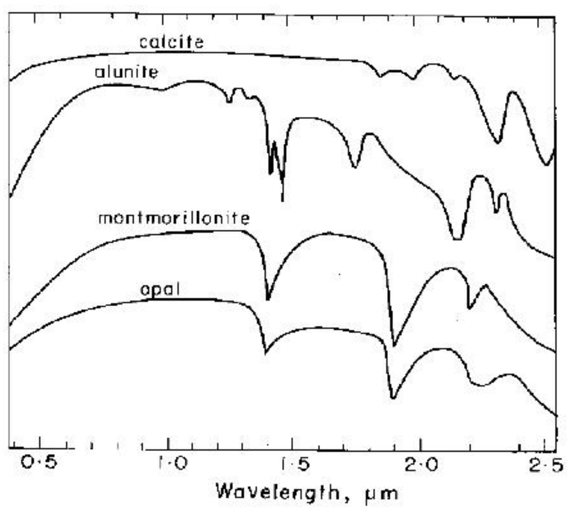

Fig. 7: Spectral characterestcs of common geothermal indicator minerals in the visible to infrared region (modified after Calvin *et al.*, 2005)

the known spring's site. In particular, this data provided very detailed information on the location and temperature of hot springs and sources of more diffuse geothermal outflow that were not obvious from field investigations (Haselwimmer and Parakash, 2012).

Remote assessment of geothermal heat fluxes

The most recent equation to estimate the heat flux is presented in Haselwimmer, *et al.,* 2014 as the following:

$\Phi total = \Phi ppt + \Phi geo + \Phi seep + \Phi evap + \Phi ens + \Phi rad + \Phi sun + \Phi sky \Phi total = \Phi ppt + \Phi geo + \Phi seep + \Phi evap + \Phi sens + \Phi rad + \Phi sun + \Phi sky$.

Where *Φppt*, *Φgeo*, *Φseep*, *Φevap*, *Φsens*, *Φrad*, *Φsun*, and *Φsky* are heat fluxes associated with precipitation, geothermal fluids (i.e. the hot spring heat flux), seepage, evaporation, sensible heat, emitted radiation, incoming solar radiation, and incoming long-wave radiation from the atmosphere, respectively. TIR remote sensing provides information on the extent and skin temperature of water bodies that is a key determinant of the *Φevap*, *Φsens*, and *Φrad* terms (Oppenheimer, 1997b). Oppenheimer (1997a) applied a simplified version of this model, removing *Φppt* and *Φseep* terms that were assumed to be negligible, to quantify the geothermal heat flux of six volcanic crater lakes in New Zealand, the Philippines, Indonesia, Costa Rica, and Nicaragua. The same method was applied successfully on Landsat 7 Enhanced Thematic Mapper Plus (ETM +) TIR data to estimate the geothermal heat flux associated with active mud volcanoes in Southeastern Alaska (Patrick *et al*. 2004).

Hyperspectral mapping as a proxy for geothermal systems

Hydrothermal minerals among other mineral assemblages can serve as a proxy for the presence of geothermal systems (e.g. Huntington, 1996). For example Martian *et al.,* 2004, showed that linear distributions of kaolinite and other hydro- thermal alteration minerals may be used as a proxy for fault and fracture distribution mapping within hyperspectral imagery to pin point to geothermal systems. Locating these distributions, their orientation and deter- mining their identity is key knowledge both for geothermal explorationists and for volcanologists studying the chemistry and dynamics of active vol- canic hydrothermal systems. Those minerals have spectral absorption features in the visible to thermal infrared wavelength regions related to electronic and molecular vibrations. These spectral absorption features provide the basis for mapping of these materials using multispectral and hyperspectral remote sensing that can map both active and blind geothermal systems (Kratt *et al.,* 2006). Fig. 8 shows the spectral profiles for common minerals which can be used as a proxy for geothermal systems. Spectral mapping of geothermal system is possible because geothermal-related minerals such as iron oxides, clays, sulfates and carbonates display diagnostic absorptions in the 0.4-2.5 μm range of reflected light (Clark, 1999). Spectral measurements in this range are commonly made with laboratory and field spectrometers, in addition to airborne and spaceborne imaging spectrometers deployed for mineral identification and exploration over large areas (Goetz *et al.,* 1983; Green *et al.,* 1998; Rowan *et al.,* 2003). Recent work has applied this technology specifically to geothermal exploration.

The airborne visible/infrared imaging spectrometer (AVIRIS) and the Hymap (hyperspectral mapper) sensors scanned the terrestrial surface provide spectra measurements in the 0.4-2.5 μm region which can be used to 1) locate and map areas with unique geothermal identifier minerals 2) make structural interpretations and focus more detailed field work. Martini (2002 and 2004) and Kratt (2005) used Hymap data (http://www.hyvista.com) to recognize mineral distributions related to structurally-controlled upwelling geothermal fluids. The Hymap instrument uses 127 contiguous channels to resolve mineral and vegetation spectra in the 0.45-2.5 μm range for each image pixel.

Challenges and way forward

The success of remote sensing based mapping relies on the spectral and spatial resolutions of the selected dataset, data correction and the performance and adequacy of the processing algorithms. The un-mixing of the spectra is still a standing challenge in hyperspectroscopy, whereas TIR remote sensing approach has been limited by the difficulty in modeling the diurnal heating effects caused by the sun. An example of where this is a challenge is the main sinter terrace at Steamboat Springs, NV, where a conventional pre-dawn thermal image does not detect a thermal anomaly in spite of numerous fumaroles being present (Coolbaugh *et al.,* 2006). The terrace has a relatively high albedo and reflects much of the sun's energy during the day. It has a low thermal inertia because of its high porosity and a currently low water table, and consequently cools off quickly at night. Surface cover is always a challenge for both spectral and thermal approaches. However, it is believed that surface cover could have some direct or under certain circumstances indirect geothermal signatures. Those signatures include certain mineral assemblage's e.g. sinter, carbonate and hydrothermal alteration minerals, such as clays and sulfates, which can be identified by their unique spectral signatures from visible through infrared wavelengths. Surface cover could act as an insulator or conductor to heat flux. Research should focus on the those challenges noted earlier and the way forward should emphases on 1) applying the thermal and hyperspectoscopy remote sensing to explore direct and indirect regional geothermal signatures and correlate finding with ground truthing and well databases (oil and water) thermal information, 2) develop algorithms to scale multi-thermal sensors data of different spatial resolutions, 3) evaluate previous drillings (boreholes) data and geophysical studies for reservoir characterization and additional verification purposes, 4) relate subsurface data and observations to remote sensing signals i.e. factor in subsurface heat contribution

CONCLUSION

Prospecting involves not only identifying hot geothermal bodies, but also low-density, cost effective regions to drill and already constituted plumbing systems inherent within the subsurface. This information allows for higher success rates in geothermal plant production as well as lower drilling costs. The paper gave a short review of the main remote sensing approaches used to map features of geothermal systems and associated geostructure. Emphasis was put on direct methods like the TIR approaches and on the hyperspectral methods. It also illustrated some principles underlying the successful application of those approaches. The study found that thermal infrared (TIR) remote sensing data can be employed to delineate temperature anomalies associated with surface geothermal attributes such as hot springs, geysers, fumaroles, and heated ground. This approach has been employed as a cost-effective tool for geothermal exploration of large areas making subsequent selection of targets for further exploration using ground-based surveys possible task. TIR remote sensing has been used also to classify and long-term monitoring of thermal features of geothermal systems and associated geostuctures.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

REFERENCES

Baldridge, A.M.; Hook, S.J.; Grove, C.I.; Rivera, G., (2009). The ASTER spectral library version 2.0. Remote Sens. Environ. 113: 711–715 (**5 pages**).

Bertani, R., (2012). Geothermal power generation in the world 2005-2010 update report. Geothermics, 41: 1-29 (**29 pages**).

Blackwell, D.; Negraru., P.; Richards, M., (2006). Assessment of the enhance geothermal system resource base of the United States, Nat. Res. Res., 15(4): 283-308 (**6 pages**).

Bromley, C.; van Manen, S.; Mannington, W., (2011). Heat flux from steaming ground: Reducing uncertainties. In Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Calvin, W.M., Coolbaugh, M., Kratt, C., and Vaughan, R. (2005) Application of remote sensing technology to geothermal exploration, in Rhoden, H.N., Steininger, R.C., and Vikre, P.G., eds., Geological Society of Nevada Symposium: Window to the World, Reno, Nevada, May 2005, 1083–1089.

Carr, B.; Heasler, H.; Jaworowski, C., (2009). Airborne reconnaissance of hydrothermal areas using daytime thermal infrared imagery. Portland GSA Annual Meeting.

Clark, R. N., (1999). Spectroscopy of rocks and minerals and principles of spectroscopy. Remote Sensing for the Earth Sciences: Manual Remote Sens., 3 ed., 3: 3-58 (**55 pages**).

Clauser, C.; Huenges, E., (1995). Thermal conductivity of rocks and minerals: Rock physics and phase relations, A handbook of physical constants, American Geophysical Union, 105-126 (**22 pages**).

Coolbaugh, M.F.; Kratt, C.; Fallacaro, A.; Calvin, W.M.; Taranik, J.V., (2007). Detection of geothermal anomalies using advanced spaceborne thermal emission and reflection radiometer (ASTER) thermal infrared images at Bradys Hot Springs, Nevada, USA. Remote Sens. Environ. 106(3): 350-359 (**10 pages**).

Dean, K.G.; Dehn, J.; Papp, K.R.; Smith, S.; Izbekov, P.; Peterson, R.; Steffke, A., (2004). Integrated satellite observations of the 2001 eruption of Mt. Cleveland, Alaska. J Volcanol. Geotherm. Res. 135 (1): 51–73 (**23 pages**).

Dehn, J.; Prakash, A.; Dean, K., (2006). Unpublished final FLIR report for chena hot springs resort. Technical report, in Haselwimmer, C.; Prakash, A.; Holdmann, G., (2013): Quantifying the heat flux and outflow rate of hot springs using airborne thermal imagery Case study from Pilgrim Hot Springs, Alaska. Remote Sen. Environ. 136: 37-46 (**10 pages**).

DiPippio, R., (2005). Geothermal power plants: Principles, applications and case studies. Butterworth-Heinemann: Elsevier, Oxford, England, (**600 pages**).

Eneva, M.; Coolbaugh, M., (2009). Importance of elevation and temperature inversions for the interpretation of thermal infrared satellite images used in geothermal exploration. GRC Transactions, 33.

Eneva, M.; Coolbaugh, M.; Combs, J. (2006). Application of satellite thermal infrared imagery to geothermal exploration in east central California. GRC Transactions 30.

Goetz, A.F.H.; Rock, B.N.; Rowan, L.C., (1983). Remote sensing for exploration: An overview, Econom. Geol., 78: 573–590 (**18 pages**).

Green, R. O.; Eastwood, M. L.; Sarture, C. M.; Chrien, T. G.; Aronsson, M.; Chippendale; B. J., Faust, J. A.; Pavri, B. E.; Chovit, C. J.;Solis, M.; Olah, M. R.; and Williams, O., (1998). Imaging spectroscopy and the airborne visible/ infrared imaging spectrometer (AVIRIS). Remote Sens. Environ. 64: 227-248 (**12 pages**).

Gupta, H.; Roy S., (2007). Geothermal energy: An alternative resources for the 21st Century. 1st. ed., Elsiver Publisher, UK, pp 297.

Gutierrez, F.J.; Lemus, M.; Parada, M.A.; Benavente, O.M.; Aguilera, F.A., (2012). Contribution of ground surface altitude difference to thermal anomaly detection using satellite images: Application to volcanic/geothermal complexes in the Andes of Central Chile. J. Volcanol. Geotherm. Res. 237: 69–80 (**12 pages**).

Hackwell, J. A.; Warren, D.W.; Bongiovi, R.P.; Hansel, S.J.; Hayhurst, T.L.; Mabry, D.J.; Sivjee, M.J.; Skinner, J.W., (1996). LWIR/MWIR imaging hyperspectral sensor for airborne and ground-based remote sensing, SPIE.

Haselwimmer, C. E.; Prakash, A.; Holdmann, G., (2011). Geothermal exploration at pilgrim hot springs. Alaska using airborne thermal infrared remote sensing. Geothermal Resource Council Annual Meeting 2011, San Diego, USA.

Haselwimmer, C.; Prakash, A., (2012). Chapter 17 - Thermal infrared remote sensing of geothermal systems. in thermal remote sensing, edited by Kuenzer, C., Springer and Praxis, ~500 p.

Haselwimmer, C.; Prakash, A.; Holdmann, G., (2013): Quantifying the heat flux and outflow rate of hot springs using airborne thermal imagery Case study from Pilgrim Hot Springs, Alaska. Remote Sens. Environ. 136: 37-46 (**10 pages**).

Henry, C. D., (1979). Geologic setting and geochemistry of thermal water and geothermal assessment, Trans-Pecos Texas: The University of Texas Bureau of Economic Geology, Report of Investigation 96, 48 p.

Hodder, D. T., (1970). Application of remote sensing to geothermal prospecting. Geothermics, 2 (1): 368–380 (**13 pages**).

Hook, S.J.; Myers, J.; Thome, K.J.; Fitzgerald, M.; Kahle, A.B., (2001). The MODIS/ASTER airborne simulator (MASTER). A new instrument for earth science studies. Remote Sens. Environ. 76: 93–102 (**10 pages**). http://www.unr.edu/geothermal/pdffiles/CalvinGSN05.pdf

Huntington, J.F., (1996). The role of remote sensing in finding hydrothermal mineral deposits on earth. Ciba Foundation Symposium 202 – Evolution of hydrothermal ecosystems on earth. John Wiley & Sons, Ltd.: 214-235 (**22 pages**).

Jaworowski, C.; Heasler, H.; Neale, C.; Cardenas, B.; Sivarajan, S., (2009). Using night-time, thermal infrared, imagery to remotely monitor the hydrothermal system at hot spring basin, Yellowstone National Park. Rocky Mountain Section - 61st. Annual Meeting, 11-13 May.

Kratt, C. B., (2005). Geothermal exploration with remote sensing from 0.45 – 2.5 μm over Brady-Desert Peak, Churchill County, Nevada. M.Sc. Thesis, University of Nevada, Reno.

Kratt, C.; Coolbaugh, M.F.; Calvin, W.M., (2006). Remote detection of quaternary borate deposits with ASTER satellite imagery as a geothermal exploration tool, Geotherm. Res. Council Trans., 30: 435-439 (**5 pages**).

Martini, B. A.; Hausknecht, P.; Pickles, W. L.; Cocks, P.A., (2004). The northern fish lake valley pull-apart basin: Geothermal prospecting with hyperspectral imaging. Geotherm. Res. Council Trans., 28: 663-667 (**5 pages**).

MODIS Thermal Infrared Data. AGU Fall Meeting (2011). San Francisco, USA.

Mongillo, M., (1994). Aerial thermal infrared mapping of the Waimangu- Waiotapu Geothermal Region, New Zealand." Geothermics 23(5/6): 511- 526 (**16 pages**).

Mongillo, M.A.; Graham, D.J., (1999). Quantitative evaluation of airborne video TIR survey

Oppenheimer, C. (1997a). Remote sensing of the color and temperature of volcanic lakes. Int. J. Remote Sens. 18 (1): 5–37 (**29 pages**).

Oppenheimer, C., (1997b). Ramifications of the skin effect for Crater Lake heat budget analysis. J. Volcan. Geotherm. Res., 75 (1–2): 159–165 (**6 pages**).

Patrick, M.; Dean, K.; Dehn, J., (2004). Active mud volcanism observed with Landsat 7 ETM+ J.f Volcan. Geotherm.Res.,131 (3–4): 307 320 (**5 pages**).

Prata, A.J.; Grant, I.F., (2001). Determination of mass loadings and plume heights of volcanic ash clouds from satellite data. CSIRO Atmospheric research technical paper, 48: 41 pp.

Rowan, L.C.; Mars, J.C.; Simpson, C.J., (2005). Lithologicmapping of the Mordor, NT, Australia ultramafic complex by using the advanced spaceborne thermal emission and reflection radiometer (ASTER). Remote Sens. Environ. 99 (1): 105–126 (**12 pages**).

Rybach, L., (1981). Geothermal systems, conductive heat flow, geothermal anomalies; *in* Geothermal systems: principles and case histories. Rybach, L.; Muffler,j.P., John Wiley & Sons.

Sabine, C.; Realmuto, V.J.; Taranik, J.V., (1994). Quantitative estimation of granitoid composition from thermal infrared multispectral scanner (TIMS) data, desolation wilderness, Northern Sierra Nevada, California. J. Geophys. Res. 99 (B3): 4261–4271 (**11 pages**).

Taranik, J.V., (1988). Application of aerospace remote sensing technology to exploration for precious metal deposits in the western United States. In: Schafer, R.W. (Ed.), Bulk Mineable Precious Metal Deposits of the Western United States, GSN Symposium Proceedings. Geological Society of Nevada, Reno, NV, 551–575 (**25 pages**).

van der Meer, F.; Hecker, C.; Ruitenbeek, F.V.; Werff, H.V.D.; Wijkerslooth, C.D.; Wechsler, C., (2014). Geologic remote sensing for geothermal exploration: A review. Int. J. Appl. Earth Observ. Geoinf., 33: 255–269 (**15 pages**).

Vaughan, R. G.; Calvin, W.M.; Taranik, J.V., (2003). SEBASS hyperspectral thermal infrared data: surface emissivity measurement and mineral mapping. Remote Sens. Environ. 85(1): 48-63 (**16 pages**).

Vaughan, R. G.; Hook, S.J.; Calvin, W.M.; Taranik, J.V., (2005). Surface mineral mapping at Steamboat Springs, Nevada, USA, with multiwavelength thermal infrared images. Remote Sens. Environ. 99(1"2): 140-158 (**19 pages**).

Wright, R., Flynn, L., Garbeil, H., Harris, A., Pilger, E., (2002). Automated volcanic eruption detection using MODIS. Remote Sens. Environ. 82 (1): 135"155 (**11 pages**).

Zhang, X.; Pazner, M.; Duke, N., (2007). Lithologic and mineral information extraction for gold exploration using ASTER data in the South Chocolate Mountains, California. ISPRS J. Photogramm. Remote Sens. 62 (4): 271"282 (**12 pages**).

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