SATELLITE REMOTE SENSING FOR HYDROTHERMAL ALTERATION MINERALS MAPPING OF SUBTLE GEOTHERMAL SYSTEM IN UNEXPLORED ASEISMIC ENVIRONMENT

ALIYU JA'AFAR ABUBAKAR

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Universiti Teknologi Malaysia

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To my Father and Mother
For their endless love and prayers,
To my beloved wife, *Asma'u,*
and my kids; *Ishaq, Abduljaleel, Zainab and Haidar*,
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ABSTRACT

Mapping prospective geothermal (GT) resources and monitoring associated surface manifestations can be challenging and prohibitively expensive in subtle systems especially when using conventional survey methods. Remote sensing offers a synoptic and cost-effective capability for identification of GT systems. The objective of this research is to refine and develop methods of identifying unconventional GT systems by evaluating the applicability of the ASTER, Landsat 8 and Hyperion satellite data for mapping hydrothermal alteration indicator minerals as proxy for detecting subtle GT targets in unexplored aseismic settings. The study area is Yankari Park in North Eastern Nigeria, characterized by the thermal springs; Wikki, Mawulgo, Gwana and Dimmil. *Spectral Angle Mapper* (SAM), *Linear spectral Unmixing* (LSU) and *Mixture Tuned Matched Filtering* (MTMF) were comparatively evaluated by using image derived spectra and corresponding library spectra for mapping pixel abundance of GT indicator minerals in a novel and efficient manner. The results indicated that employing image derived spectra from field validated and laboratory verified regions of interest as reference, gives more accurate results than using library spectra around known alteration zones remotely detectable on the imagery. The MTMF provided high performance subpixel target detection with an accuracy of 50-100% and 70-100% subpixel abundance for *argillic-phyllic-silicic* and *propylitic* alteration mineral assemblages respectively, as compared to less than 10% for the same endmembers when using library spectra. The MTMF is thus best suited for mapping alterations associated with subtle GT systems than the less selective LSU. The per-pixel SAM was unsuitable for target detection of alteration indicators of interest with poor overall accuracy of 33.81% and 0.24 Kappa coefficient at 0.02 radian angle. Results of mapping thermally anomalous pixels do not conform to known locations of the thermal springs signifying the limitations of the current thermal sensors in mapping low temperature GT systems even at 60m spatial resolution. However, examining the spatial correlation of the anomaly areas with the major geologic structure systems from geological map of the study area indicates a close affinity between them and with previously reported thermal gradients within heat insulating sedimentary formations. This study establishes the integrative applicability of Multispectral and Hyperspectral data for mapping subtle GT targets in unexplored regions using in-situ validated alteration mineral mapping and thermal anomaly detection. This has significant implication for the GT green energy industry as the developed methods and GT prospect map could aid the prefeasibility stage narrowing of targets for in-depth geophysical, geochemical, geothermometric and related surveys.

ABSTRAK

Memetakan sumber prospek geoterma (GT) dan pemantauan manifestasi permukaan berkaitan adalah sangat mencabar dan mahal terutamanya apabila melibatkan sistem geoterma kurang ketara menggunakan kaedah pemetaan konvensional. Penginderaan jauh menawarkan keupayaan sinoptik dan kos efektif untuk mengenal pasti sistem GT. Objektif kajian ini adalah untuk memperhalusi dan membangunkan kaedah mengenal pasti sistem GT yang tidak konvensional dengan menilai pemakaian data satelit ASTER, Landsat 8 dan Hyperion untuk pemetaan mineral penunjuk hidroterma sebagai proksi untuk mengesan sasaran GT yang halus dalam tetapan tidak-seismik yang belum diterokai. Kawasan kajian ialah Taman Yankari di Nigeria Timur Utara, yang dicirikan oleh beberapa mata air panas Wikki, Mawulgo, Gwana dan Dimmil. Teknik pengelasan data digital *Spectrum Angle Mapper* (SAM), *spectrum Linear Unmixing* (LSU) dan *Mixture Tuned Matched Filtering* (MTMF) dinilai secara relatif dengan menggunakan spektrum yang diperoleh dari imej dan spektrum rujukan yang bersesuaian untuk pemetaan semua piksel mineral penunjuk GT. Hasil kajian menunjukkan bahawa menggunakan spektrum yang diperoleh dari imej yang telah disahkan oleh analisis spektrum makmal bagi kawasan yang diselidiki memberi hasil yang lebih tepat daripada spektrum rujukan di sekitar zon perubah. MTMF menyediakan pengesanan sasaran sub-piksel prestasi tinggi dengan ketepatan 50-100% dan 70-100% sub-piksel yang berlimpah untuk perhimpunan galian alahan *argillic-phyllic-silicic* dan *propylitic* masing-masing, berbanding kurang daripada 10% untuk pengguna akhir yang sama apabila menggunakan spektrum rujukan. Oleh itu, MTMF adalah paling sesuai untuk pemetaan perubahan yang berkaitan dengan sistem GT-kurang ketara berbanding LSU yang kurang selektif. Sampel per piksel tidak sesuai untuk mengesan sasaran penunjuk perubahan dengan ketepatan keseluruhan 33.81% dan 0.24 pekali Kappa pada 0.02 radian sudut. Keputusan pemetaan piksel anomali termal tidak sesuai dengan lokasi yang diketahui dari mata air termal yang menandakan keterbatasan sensor termal semasa dalam pemetaan sistem GT suhu rendah walaupun pada resolusi spatial 60 m. Walau bagaimanapun, mengkaji korelasi spatial bagi kawasan-kawasan anomali dengan sistem struktur geologi utama dari peta geologi di kawasan kajian menunjukkan persamaan rapat bagi keduanya dengan kecerunan haba yang dinyatakan sebelum ini dalam kajian pembentukan sedutan haba. Kajian ini menunjukkan penerapan integratif data multispektral dan hiperspektral untuk pemetaan sesaran GT kurang ketara di kawasan yang belum diterokai, boleh di tentu sah melalui sampel lapangan dan pengesanan anomali termal. Hasil kajian mempunyai implikasi yang ketara untuk sumbangan ke industri tenaga hijau GT kerana kaedah yang dibangunkan dan peta prospek GT dapat membantu penelitian terperinci tahap sesaran haba bagi geofizik, geologi, geokimia, geotermometri dan kaji selidik yang berkaitan.

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LIST OF ABREVIATIONS

ASD	-	Analytical Spectral Device
ASTER	-	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS	-	Advanced Visible & Infrared Imaging spectrometer
BHT	-	Borehole Temperature
DCS	-	Decorrelation Stretch
EGS	-	Enhanced Geothermal System
EMS	-	Electromagnetic Spectrum
ENVI	-	Environment for Visualizing Images
ETM+	-	Enhanced Thematic Mapper+
FLAASH	-	Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes
FLIR	-	Forward Looking Infrared Radiometer
FPCS	-	Feature-oriented Principal Component Selection
GCP	-	Ground Control Points
GPS	-	Global Positioning System
GHF	-	Geothermal Heat Flux
GT	-	Geothermal
GIS	-	Geographical Information Systems
HYMAP	-	Hyperspectral Mapper
HyspIRI	-	Hyperspectral Infrared Imager

IARR	-	Internal Average Relative Reflection
IFOV	-	Instantaneous Field of View
LUT	-	Look-Up-Table
LSE	-	Land Surface Emissivity
LST	-	Land Surface Temperature
LSU	-	Linear Spectral Unmixing
LWIR	-	Long Wave Infrared
MAGI	-	Mineral and Gas Identifier
MNF	-	Minimum Noise Fraction
MODIS	-	Moderate Resolution Imaging Spectroradiometer
MTMF	-	Mixture Tuned Matched Filtering
NDVI	-	Normalized Difference Vegetation Index
PCA	-	Principal Component Analysis
PPI	-	Pixel Purity Index
ROI	-	Region of Interest
SAM	-	Spectral Angle Mapper
SCA	-	Single Channel algorithm
SEBASS	-	Spatially Enhanced Broadband Array Spectrograph
SWIR	-	Shortwave Infrared
TIMS	-	Thermal Infrared Multispectral Scanner
TIR	-	Thermal Infrared
USGS	-	United States Geological Survey
UTM	-	Universal Transverse Mercator
VNIR	-	Visible Near Infrared
XRD	-	X-Ray Diffraction

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Globally, there is a serious energy concern. This is partly as a result of the combustion of fossil based carbon fuels causing climate change, global warming and environmental pollution (Seinfeld and Pandis, 2012). According to the International Energy Agency (IEA), the total world energy comes from 80% fossil fuels, 10% biofuels, 5% nuclear and 5% renewable (hydro, wind, solar, geothermal), only 18% of the total world energy was in the form of electricity (Obama, 2017). In addition, fluctuating oil prices due to security concerns in mostly politically unstable oil producing regions and the exhaustibility of greenhouse gas emitting fuels such as oil, natural gas, coal etc. has prompted a search for alternative energy sources. Consequently, the need for renewable energy systems which are not only reliable but also environmentally sustainable has become imperative (Omer, 2008).

While most advanced countries like the United States, United Kingdom are drawn into the race for renewable energy and alternatives as a result of climate change and the need to move towards a low-carbon society, third world countries are yet to even satisfy the minimal of their energy needs (Newell and Bulkeley, 2017). There is a serious energy poverty in developing and especially poor countries in Africa (Salazar *et al.*, 2017). This further worsens environmental degradation through fuel wood extraction, deforestation, consequently reducing carbon sink and increasing global warming (Chiesa *et al.*, 2009).

A lot of progress has been made in research and innovation in renewable energy systems and technologies including solar, wind, hydropower, and bioenergy (Johansson *et al.*, 2004; Noailly and Shestalova, 2017). However, the lack of an efficient storage systems, intermittent nature and the dependence of these Energy sources on climatic fluctuations and uncertainties have been the bane of most renewable energy systems (Denholm *et al.*, 2010).

Geothermal (GT) energy (resource), which is the energy derived from the earth's heat, offers a renewable and a reliable source of energy (Glassley, 2014). However, like most renewable energies it is inherently regional and site specific, mostly associated with areas of magmatic episodes and crustal plate movements. Depending on the amount of heat that can be harnessed, GT resources have been used in many areas around the world for power, home heating, industrial/commercial, aquaculture, greenhouses, recreational/spa, balneology/medicinal therapy, tourism and several others (Lund *et al.*, 2011; Lund and Boyd, 2016). In many countries around the world such as Australia, USA, Iceland, and Japan, GT resources like hotsprings are a multi-billion dollar industry for spa/recreation, balneology among others, which attracts millions of tourists' worldwide (Clark-Kennedy and Cohen, 2017).

Renewable energies are inherently regional and site specific. While solar and wind energy could be harnessed effectively in sunny and windy areas, geothermal potential areas have been associated with areas of crustal manifestations and magmatic episodes. Identifying new prospective areas of geothermal resources requires information on their location, depth, temperature and surface manifestations such as hot springs, fumaroles, Geysers and associated minerals (Prakash, 2012).

Remote sensing offers a great deal of data that can be used for mapping prospective geothermal locations using both optical and thermal infrared remote sensing which map GT indicator alteration minerals and detect heat and subtle temperature anomalies that serve as clues at geothermal locations. While not directly involved in the generation of energy, application of this complementary technology is in the supply of information and spectral reflectance data which when interpreted and analyzed can aid in determining the optimal location of potential targets for geothermal resource exploration, exploitation, monitoring and development (Nishar *et al.*, 2016a).

Remotely sensed satellite data such as; the thermal infrared multispectral scanner (TIMS), Advanced Space borne Thermal Emission and reflection Radiometer (ASTER), MODIS/ASTER or MASTER and Landsat TM, Landsat 7 ETM+ and Landsat 8, have thermal infrared (TIR) bands, and have been used in the prefeasibility stages of geothermal exploration and monitoring GT systems (Calvin *et al.,* 2015; Heasler *et al.,* 2009). The Thermal Infrared (TIR) portion of the electromagnetic spectrum (EMS) (10um to 12.5um) offers the possibility of sensing surface temperature anomalies and heat fluxes emitted from prospective GT locations which serves as targets for exploration and monitoring (Bromley *et al.*, 2011; Coolbaugh *et al.*, 2007; Dean *et al.*, 1982; Eneva *et al.*, 2006; Fitts, 2013; Haselwimmer *et al.*, 2013; Heasler *et al.*, 2009; Hochstein and Dickinson, 1970; Hodder, 1970; Mia *et al.*, 2014; Nishar *et al.*, 2016b; Prakash, 2012; Qin *et al.*, 2011; Tian *et al.*, 2015)

Surface manifestations of GT areas have been successfully detected and mapped using hyperspectral data including; spatially enhanced broadband array spectrograph-SEBASS, hyperspectral mapper-HYMAP, ProspecTIR, advanced visible & infrared imaging spectrometer-AVIRIS and multispectral data such as ASTER, Landsat and MASTER for remote sensing of hydrothermally altered mineral indicators as proxy for exploration of GT systems (Calvin *et al.*, 2015; Hanson *et al.*, 2014; Hellman and Ramsey, 2004; Kratt *et al.*, 2006a; Kratt *et al.*, 2010; Kratt *et al.*, 2006b; Kruse, 2002; Reath and Ramsey, 2013; Van der Meer *et al.*, 2012; Vaughan *et al.*, 2003; Vaughan *et al.*, 2005; Waswa, 2017; Adams *et al.*, 2017)

The techniques involved in GT exploration using remote sensing, despite being complementary to in-depth geological surveys, has nevertheless established itself as an invaluable step in the prefeasibility stages of GT mapping due to its synoptic capability of covering large and inaccessible areas cost effectively and by narrowing targets prior to a substantial survey. However, while thermal infrared imagery have been used for sensing temperature anomaly related to GT systems, its usefulness in exploration has been constrained by the requirement for an extended calibration for detecting subtle temperature anomalies (Calvin *et al.*, 2015). Consequently, to date surface thermal anomalies have only been detected within proximate areas of known surface expressions like geysers, hotsprings and fumaroles (Coolbaugh *et al.*, 2007).

Hydrothermal systems are GT systems characterised with hot water, steam and permeable faults which serve as conduits for fluid circulation. Geysers and hotsprings are typical examples of hydrothermal systems (Heasler *et al.*, 2009). The nature of active hydrothermal processes in many GT systems is similar to the processes that generate alteration mineral deposits (Carranza *et al.*, 2008). Thus mineral deposit exploration concepts are applicable and have been used for exploration of GT resources for example by identifying Hydrothermal Alteration (HA) zones and minerals (Bogie and Lawless, 2000).

Detailed mineralogical studies of GT fields have been done by previous studies which revealed an array of alteration minerals related to GT settings (Calvin *et al.*, 2015; Littlefield and Calvin, 2014; Vaughan *et al.*, 2003). The use of portable field spectrometers and laboratory spectral libraries have also been employed in studies to validate results from remotely sensed data (Kratt *et al.*, 2006b; Calvin and Pace, 2016a). The class of common alteration minerals associated with GT systems which are detectable in remote sensing are limited. Many minerals have diagnostic spectral properties and features such as; band center, strength, shape and width which are used to identify mineral species with high confidence (Hunt, 1977). Laboratory and remote sensing spectral data are usually separated into wavelength ranges on the basis of their absorption features and the atmospheric windows through which the earth surface is measured (Calvin *et al.*, 2015). In the visible near infrared (VNIR) and short-wave infrared (SWIR) wavelengths (0.4 to~2.5 um), moderate and low-temperature surfaces are sensed because of the sunlight they reflect (Clark *et al.*, 2003). Absorption features occur as a result of electronic orbital configuration of transition metals (generally iron or copper) in various crystallographic sites and from the combination and overtones of molecular vibrations from species such as hydroxyl, water, carbonate, and sulfate (Clark *et al.*, 2003). This region of the electromagnetic spectrum is most sensitive to iron oxides, oxy-hydroxides, and ligands resulting from high or low temperature alteration (Clark, 1999). The ability to readily discriminate minerals by their unique spectral characteristics has generally been used as the basis for the techniques applied in economic mineral exploration (Pour and Hashim, 2015b) and in particular, the basis for application in geothermal exploration and mapping using associated hydrothermally altered minerals as surrogates (Calvin *et al.*, 2015).

This study evaluated the applicability and performance of satellite multispectral and hyperspectral remote sensing data for mapping subtle GT systems in an uncharted tropical savanna region. Subtle GT systems are characterized by low temperature thermal springs, and sometimes may not necessarily have clear materialization of GT manifestations but however, indicate signs, imprints and relics of past GT activity such as altered rock deposits that can be used to identify and or infer on their characteristics. The Yankari Park is an area in northeastern Nigeria characterized by several hotsprings and consequently hydrothermally altered rocks. These provides a suitable test area for investigation of subtle GT features which are challenging to detect using conventional methods. Advanced and innovative digital image processing techniques and spectral information extraction algorithms are assessed in sieving out relevant data to explore the peculiarities provided by this unique environmental setting.

1.2 Problem Statement

The long term economic progress and development of a country is usually hinged on its ability to provide unhindered supply of not only accessible and affordable but also environmentally friendly energy sources (Brimmo *et al.*, 2017). Despite having a population of over 170 million, Nigeria produces only 4000MW of electricity compared to Brazil, which produces 24 times as much for almost similar population (Garba, 2017). This challenge emphasized the need to explore alternative renewable energy sources. Consequently, the country is seriously hampered in terms of economic development and relies mostly on epileptic thermal to hydropower sources. This is notwithstanding efforts towards renewable alternatives which have largely remained at experimental stages (Adenikinju, 2008; Emodi and Yusuf, 2015). Geothermal energy could be an important long term vision for clean sources of energy (Abraham *et al.,* 2015). Several GT manifestations have been identified circumstantially and are mostly exploited for direct use (Abdullahi *et al.*, 2014). GT resources could provide sustainable alternatives if new potential sites can be identified. Surprisingly however, there has been limited studies to evaluate GT prospects using remote sensing and geospatial techniques in spite of their cost effectiveness and synoptic capabilities. The few previous GT assessment studies in the country have been focused on using conventional methods which are cumbersome, time consuming and expensive with small area coverage and undependable outcomes (Kurowska and Krzysztof, 2010; Nwankwo and Ekine, 2009; Nwankwo and Shehu, 2015). Consequently, an evaluation study of this nature is imperative, timely and worthwhile.

In general, mapping and identifying prospective GT resources can be challenging. This is especially the case in subtle systems not easily identifiable using conventional survey techniques. As observed from literature, different methods have been employed using remote sensing to identify GT targets, including; mapping thermal anomalies, minerals by proxy and structural faults (Coolbaugh *et al.*, 2007; Eneva *et al.*, 2006; Haselwimmer *et al.*, 2013; Hellman and Ramsey, 2004; Hochstein and Dickinson, 1970; Hodder, 1970; Kratt *et al.*, 2006a; Littlefield and Calvin, 2014; Mia *et al.*, 2014; Mongillo, 1994; Calvin *et al.*, 2015; Prakash, 2000; Qin *et al.*, 2011; Vaughan *et al.*, 2003; Vaughan *et al.*, 2005; Macharia *et al.*, 2017; Saepuloh *et al.*, 2015; Saepuloh A. *et al.*, 2012). These studies are mostly in volcanic and tectonically active locations. It is however, not fully understood how these techniques could be implemented in aseismic environments with characteristically subtle GT features (Littlefield and Calvin, 2014). This signifies the need for more studies in such regions and their identification using state of the art techniques of remote sensing and spectroscopy. This is imperative, particularly with the promising advances expected in the enhanced geothermal systems (EGS) which could make many regions of the world exploitable for GT renewable resources (Olasolo *et al.*, 2016) and the recent appreciable global increase in areas of GT exploitation and direct use (Lund *et al.*, 2011; Lund and Boyd, 2016). This study is thus premised on the need to improve and refine methods of mapping unconventional GT targets in order to fully realize the potentials of GT resources as a competitive renewable alternative with diverse exploitive uses.

In the context of Hydrothermal alteration mapping as proxy for identification of indicator minerals for characterization of GT systems, there has been in the last few years a large increase in performance especially for narrowing targets in the prefeasibility stages of exploration (Calvin *et al.,* 2015; Calvin and Pace, 2016; Van der meer *et al.,* 2014). This is as a result of the successful application of both multispectral and hyperspectral airborne and spaceborne remotely sensed data coupled with innovative spectral information extraction algorithms for robust characterization of associated surface compositional features in proximate areas of GT systems (Hamilton *et al.*, 2016). However, severe remaining limitations still exist in terms of the requirement for the use of library spectra as reference for analysis as observed from most previous studies (Kratt *et al.*, 2010) (Kennedy-Bowdoin *et al.*, 2004; Kratt *et al.*, 2006a; Kratt *et al.*, 2010; Kratt *et al.*, 2006b; Kruse, 2013; Littlefield and Calvin, 2014; Nash *et al.*, 2004; Reath and Ramsey, 2013; Vaughan *et al.*, 2003; Vaughan *et al.*, 2005). Hydrothermally altered minerals rarely occur purely to match its corresponding library spectra in all situations and in peculiar environmental settings because rock alteration vary from one region to another depending on prevailing conditions which results in unique hydrothermal alteration (Masoumi *et al.*, 2017). Consequently variable mineral mixtures may result which could affect the diagnostic spectral reflectance or emittance characteristics of endmembers of interest (Hosseinjani and

Tangestani, 2011). Thus, Surface components in unique settings may not be adequately represented in existing spectral libraries which in most cases contain modeled spectra that are acquired and generated under controled conditions different from those of satellite image data (Hosseinjani and Tangestani, 2011). Hydrothermal alteration mapping of GT systems as proxy requires endmember extraction for both linear and non-linear unmixing using image and or modeled spectra, this is however, still an ongoing effort and not a fully resolved problem (Boardman and Kruse, 2011). The use of verified image spectra in unmapped regions has also not been adequately explored which could improve the accuracy of spectral analysis for mapping and narrowing potential GT sites. Based on the above identified research issues, limitations and gaps, it is arguably imperative and worthwhile to explore new insights and refine methods. This research proposed an improved method of mapping subtle GT systems by exploring and evaluating the utility of image endmember spectra extracted from regions of interest (ROIs) which have been field validated and laboratory verified for spectral analysis, as compared to corresponding library spectra.

1.3 Research Objectives

The aim of this study is to evaluate the applicability of satellite multispectral and hyperspectral remote sensing data in mapping hydrothermal alteration indicators and anomalies as proxy for characterization of subtle GT systems in unexplored aseismic settings.

The specific objectives of the study are:

i. To identify hydrothermal alteration zones by applying image transformation methods to VNIR+SWIR+TIR bands of Landsat 8 and ASTER Multispectral data at regional scale.
ii. To discriminate/map hydrothermal alteration indicator mineral assemblages associated with geothermal systems using spectral per-pixel

and sub-pixel mapping techniques to SWIR & TIR bands of ASTER data at district scale.

iii. To examine and identify specific alteration indicator minerals of geothermal activity using EO-1 Hyperion hyperspectral data at district scale.

iv. To detect and map temperature anomalies associated with thermal springs using the Single Channel Algorithm (SCA) for Land Surface Temperature retrieval on Landsat 7 ETM+ thermal band.

v. To verify image processing results through; field validations, laboratory analysis, accuracy assessments and integrate the results using GIS into a geothermal prospect map.

1.4 Scope of the study

1. This study investigated subtle GT systems by mapping associated hydrothermal alteration minerals as proxy and detecting thermal anomalies. The study is confined to the identification of specific alteration indicator mineral assemblages such as; clays, sulfates, carbonates which mostly manifest diagnostic spectral features in the shortwave infrared (SWIR) and silicates in the thermal infrared (TIR) region of the electromagnetic spectrum. The visible (VNIR) portions of the spectrum is however used in some initial stages for qualitative mapping to sieve out background spectral information such as vegetation and for identification of secondary diagnostic spectral features of indicator minerals. Analysis of thermal anomalies is confined to the use of the TIR for land surface temperature (LST) retrieval, however, related optical bands are also used for Normalized Difference Vegetation Index Analysis.

2. The study employed 14 bands of ASTER Level 1B, 13 bands of Landsat 8, Landsat 7 ETM+ thermal band 6 and 162 bands of EO-1 Hyperion satellite data. The multispectral data covers the Yankari Park and its environs including a whole Landsat 8 and a mosaicked ASTER scene. The hyperspectral Hyperion

covers the southwestern part of the Yankari Park study area in Northeastern Nigeria. Details of acquired data characteristics is given in chapter 3.

3. Relevant softwares were employed for analysis. The ENVI (Environment for Visualizing Images) version 5.1 (Classic and Standard) was used for image rectification and detailed digital image processing, spectral information extraction using the Spectral Hour Glass approach, creation and comparison of spectral libraries and production of raster maps. The ArcGIS version 10.2 was used for thermal anomaly analysis, creation of shapefile and digitization, conversion of raster maps to vector formats, and final data integration and visualization.

4. Field survey was comprehensively done to validate remote sensing and image processing results. This involved the use of hand held GPS MONTERRA[@] to identify locations where rock samples were obtained for laboratory analysis and identifying hydrothermal alteration and GT related minerals in the samples. Samples from hot spring sites such as altered rocks were analyzed using X-Ray Diffraction (XRD) and Analytical Spectral Device (ASD) spectroradiometer equipment. Photographs were taken of the geomorphological features, rocks and hydrothermal alteration at the hot spring sites.

1.5 Significance of Study

The study made significant contribution in terms of improving the techniques for GT exploration, monitoring and narrowing of targets at the prefeasibility level especially in unexplored regions characterized by subtle anomalous features which are very difficult to identify using conventional techniques. The use of available but improved spectral and spatial resolution satellite data in mapping GT features in regions where expensive airborne surveys are not affordable could encourage further interest in GT characterization and eventual inclusion of GT resource exploitation for either power or for other resource utilization such as; tourism, industrial, commercial, greenhouses, agricultural, balneology, medicinal therapy and recreational purposes. The Yankari Park serves as an important test ground for evaluating satellite multispectral and hyperspectral data to help introduce a geospatial component to earlier GT assessment efforts which have largely been conventional, thus showcasing and encouraging further investigations in similar environmental settings elsewhere. Mapping suitable targets synoptically and cost effectively as applied and demonstrated in this study using satellite remote sensing data, geographic information system tools and innovative digital image processing techniques could usher in a renewed interest and aid decision making in GT resource exploration and exploitation. This is especially so in less developed countries in dire need of alternative sources of energy and economic development such as Nigeria. Recently, it was established that there are no comprehensive data on renewable resources especially GT in Nigeria and the few available data are incomplete and outdated (Brimmo *et al.*, 2017). This indeed is a challenge that foreshadow any practical investments in the country's energy sector. Hence there is the urgent need for nationwide resource investigations and assessments as a policy to effect appropriate enabling factors to attract investments. This study is also premised in furtherance of such a call.

In general, this research has significantly contributed to new knowledge by improving our understanding as regards the applicability of satellite sensors in mapping hydrothermal features and the effectiveness of spectral characterization of subtle GT systems using spectral matching and sub-pixel abundance estimation of associated surface compositional features by employing in-situ verified image derived spectra especially in uncharted regions. The study discovered that surface alteration mapping and detection of temperature anomalies in relation to fault structures can serve as a significant prefeasibility step for identification of interest areas. Consequently, identified and verified zones were subsequently integrated into a geothermal prospect map which can aid in depth geochemical, geophysical and geothermometric surveys thereby cost-effectively narrowing targets. The study also made significant contribution by extracting and updating the Yankari Park Geological Map which was unavailable previously. This was carried out using the Bauchi state geological map as reference, and field surveys guided by technical staff from the

Nigerian Geological Survey Agency and from the results of image transformations particularly BR, DCS, FPCS, ICA and MTMF analysis. The geological map serves as an important tool for identification of thermal anomalies in relation to identified major fault structure systems in the Park and can aid future related research particularly as regards; geological, lithological, geophysical, geothermometric and geothermal investigations.

1.6 Thesis outline

The thesis comprise of five chapters:

- **Chapter 1** explains a general background of the study and gives the problem statement, research objectives, and scope of the study and finally the significance of the study.
- **Chapter 2** gives a review of relevant literature in the field of applications of remote sensing in geothermal resource exploration, GT systems, hydrothermal systems and alteration, concepts and methods, remote sensing and spectroscopy, multispectral and hyperspectral sensors, spectral processing methods and models, GT mapping using alteration indicator minerals, thermal anomaly detection, spaceborne and airborne applications, Characteristic radiation spectra of Hydrothermal alteration minerals, previous studies and methods of mapping, inherent limitations of the techniques and observations on further research needs and future prospects in the field. Finally, Inferences made from the review
- **Chapter 3** describes the characteristics of the acquired satellite multispectral and hyperspectral data, instruments and methods, spectral information extraction methods used for the study, image enhancements, preprocessing and processing methods, field validations and laboratory verifications used to achieve the objectives of the study.
- **Chapter 4** describes the presentation and discussion of the results of image processing, spectral mapping, field and laboratory analysis.

- **Chapter 5** gives conclusions based on the results of the analysis and processing and recommendations for future work in the field of research.

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