

Geothermal resource assessment in shallow crust of Japan by three-dimensional temperature modeling using satellite imagery and well-logging dataset



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I would like to dedicate this dissertation to my loving parents . . .

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 50,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 80 figures. The full dissertation, in 12 point font, double space, 180 pages (PDF, 30 MB) submitted to Graduate School of Engineering, Kyoto University and available online at <http://repository.kulib.kyoto-u.ac.jp/dspace/handle/2433/8949>.

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“This is the only section that everyone who picks up your thesis will read. This is your chance to make obscure references to secret loves, damn various faculty members with faint praise, or be very mysterious by having no acknowledgments section at all so that everyone wonders what you’re hiding.”

Robert Schulman and Virginia Fox, *How to Write a Ph.D. Dissertation*

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Abstract

This dissertation focuses on geothermal resource assessment in shallow crust of Japan by combining techniques of [Three Dimension \(3D\)](#) temperature modeling using well-logging dataset and [Thermal Infrared Remote sensing \(TIR\)](#) imagery.

Renewable energy plays an important role in mitigating climate change, against global warming and ensuring self-sufficiency of energy supply, of which geothermal energy has the advantage of providing a stable energy supply and energy security. It is unaffected by weather conditions, in contrast to other renewable energy options such as solar and wind power generation. As a country located on the “Pacific ring of fire”, Japan is blessed with much geothermal resources. Japan ranked the third-rich in geothermal resources worldwide, However, only two percent is actually used for power generation, indicating large development room of geothermal energy utilization in Japan. Large part of direct use in Japan is for bathing, while [Geothermal Heat Pumps \(GHP\)](#) comprises only one percent of it. [GHP](#) is effective in mitigating the [Urban Heat Island \(UHI\)](#) phenomenon. For enhancement of the use and development of geothermal resource, accurate assessment of geothermal system including geological structure, fluid flow, and temperature distribution from the ground surface down to great depths is indispensable. In situ drilling borehole data provide the most accurate information in the exploration process. [3D](#) modeling of [Subsurface Temperature \(SST\)](#) using limited borehole data is useful for visualizing temperature distribution underground and hence is helpful in geothermal resources exploitation. On the other hand, [TIR](#) is effective in detecting surface manifestations

with thermal high anomalies in the [Land Surface Temperature \(LST\)](#). Therefore the main content of this dissertation is combining [3D](#) modeling of [SST](#) and [LST](#) for comprehensive understanding of geothermal systems and resource exploration (both [Geothermal Power Plant \(GPP\)](#) and [GHP](#)) of Japan.

All the [GPP](#) in Japan are located on a convection geothermal areas, the first main part of the dissertation was a try to find such area through interferes of borehole temperature profiles. A new index using coefficient of determination and R program to identify two types of heat transfer, conduction and convection, from borehole profiles was proposed. Most of temperature profiles follow the linear distribution and they should be conductive type. The results showed good discrimination of the two thermal transfer types. The categorization of heat transfer type map were applied to [Kriging with External Drift or trend \(KED\)](#) to improve the estimation in Chapter 5.

For an accurate assessment of geothermal resource, combination of well-logging temperature and [TIR](#) were applied to Hokkaido, northern Japan. [3D](#) modeling of [SST](#) and [LST](#) are indispensable together. [LST](#) is effective to detect high temperature anomaly zones at preliminary survey. The depth until 1,500 m is targeted for the former modeling using the 28,476 temperature data at 433 sites and a method of [KED](#). Regional [LST](#) is estimated from thirteen scenes of Landsat 8. The results showed that high temperature were distributed in most western region of Hokkaido and part of eastern region while low temperature were found in central region. Higher temperature in shallower crust made the western region and part of eastern region the high geothermal potential areas which are exactly coincident with the distribution of Quaternary volcanic rocks. In addition, on the basis of clarification of underground heat distribution according to borehole data, several [LST](#) anomalies were examined, which are considered to be high geothermal potential. [Remote Sensing \(RS\)](#), [Geographic Information System \(GIS\)](#) and geostatistics techniques were well applied in this dissertation. The combination of [3D](#) modeling

of SST using a dataset of well-logging temperature and LST from TIR is quite efficient and promising approach of geothermal resource exploration. Moreover, this combination may contribute to estimate terrestrial heat flux that is an environmental element.

To assess the deep geothermal potentials over Japan, we divided the Japan land into six zones of different geothermal systems: Hokkaido, Northeast of Honshu, Center of Honshu, Southwest of Honshu and Shikoku, Kyushu, Nansei Islands and Izu-Bonin geothermal systems based on various geological structures, fault zones and volcanic zones. The temperature distribution with a voxel resolution of $1000 \times 1000 \times 100$ m was estimated using KED method in the three dimension at the depth from 100 m of 1 km. Based on the result of the deep geothermal potentials, Eastern Hokkaido, Northeast Honshu, Center of Honshu and Southern Kyushu Island where further exploration and future exploitation of the geothermal resources is feasible in Japan were detected. Of these regions, the Northeast Honshu region owns the highest geothermal potential.

I specially developed two R software package for TIR data analysis and geostatistics in R programming language. The package for thermal infrared remote sensing image analysis and LST mapping, and the package geothermaR for spatial data analysis and geothermal resource assessment. All the source code of above R packages and R, Elisp, Bash, ~~TeX~~ source code of figures and calculations in the dissertation are freely available to download for reproducible research and continuous developing.

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Chapter 1

Introduction

“The journey of a thousand miles begins with a single step.”

Lao Tzu, *Tao Te Ching*

“How wonderful it is that nobody need wait a single moment before starting to improve the world.”

Anne Frank, *The Diary of a Young Girl* (1944)

In this introduction chapter, I firstly describe the backgrounds and motivations of the thesis. Then, follow a literature review, the originality and contributions of this thesis are introduced. Finally, I summarize the structure of this dissertation and relationship among the chapters.

1.1 Backgrounds

Geothermal is heat energy generated and stored inner the Earth. The heat sources of geothermal mainly from the radioactive nuclei decay of Uranium (^{238}U , ^{235}U), Thorium (^{232}Th), and Potassium (^{40}K) from minerals (70%), residual heat left over from the Earth's original formation (20%), friction of tectonic plates, and meteorite. Geothermal have been wildly used in many countries in the world, and the needs for geothermal energy are increasing (Table [1.1](#)).

Table 1.1 Installed geothermal electric capacity by countries over than 100 MW ^a

Ranking	Country	Capacity MW 2007	Capacity MW 2010	Capacity MW 2013	Percentage (%) of national production	Percentage (%) of global geothermal production
1	USA	2687	3086	3389	0.3	29
2	Philippines	1969.7	1904	1894	27.0	18
3	Indonesia	992	1197	1333	3.7	11
4	Mexico	953	958	980	3.0	9
5	Italy	810.5	843	901	1.5	8
6	New Zealand	471.6	628	895	13.6	6
7	Iceland	421.2	575	664	30.0	6
8	Japan	535.2	536	537	0.1	5
9	Kenya	128.8	167	215	11.2	
10	Costa Rica	162.5	166	208	14.0	
11	El Salvador	204.4	204	204	25.0	
12	Turkey	38	82	163	0.3	
13	Nicaragua	87.4	88	104	10.0	

^aData scraped using R from http://en.wikipedia.org/wiki/Geothermal_electricity

1.1.1 Needs for geothermal energy

Constant use of fossil fuel resources, which increases emission of **Greenhouse Gases (GHG)**, has brought out the big problem of atmospheric pollution and global warming. As the climate changes, extreme events are becoming more frequent on average (IPCC, 2007), which would cause large losses in social economy and health. Hence, there is a urgent necessity of decreasing the dependence on fossil fuel resources. Fig. 1.1 shows the CO₂ emission amount by different electric power generation methods. Geothermal power plants can be used to generate large quantities of electricity with much less of the harmful **GHG** emissions compared to electricity generation like coal, oil and natural gas fired plants (EGS, 2006, Chapter 8, Table 8.1).

Japan is heavily dependent on an imported primary energy supply. Oil is the leading source of energy (42.5%), followed by coal (21.5%), natural gas (17.1%), nuclear (15.4%), hydro (1.4%), biofuels and waste (1.4%), and geothermal/solar/wind (0.8%) as of 2009 reported by **International Energy Agency (IEA)**. As Japan imports the most of its energy, the government made great efforts to develop domestic energy sources, geothermal, hydro and solar energy

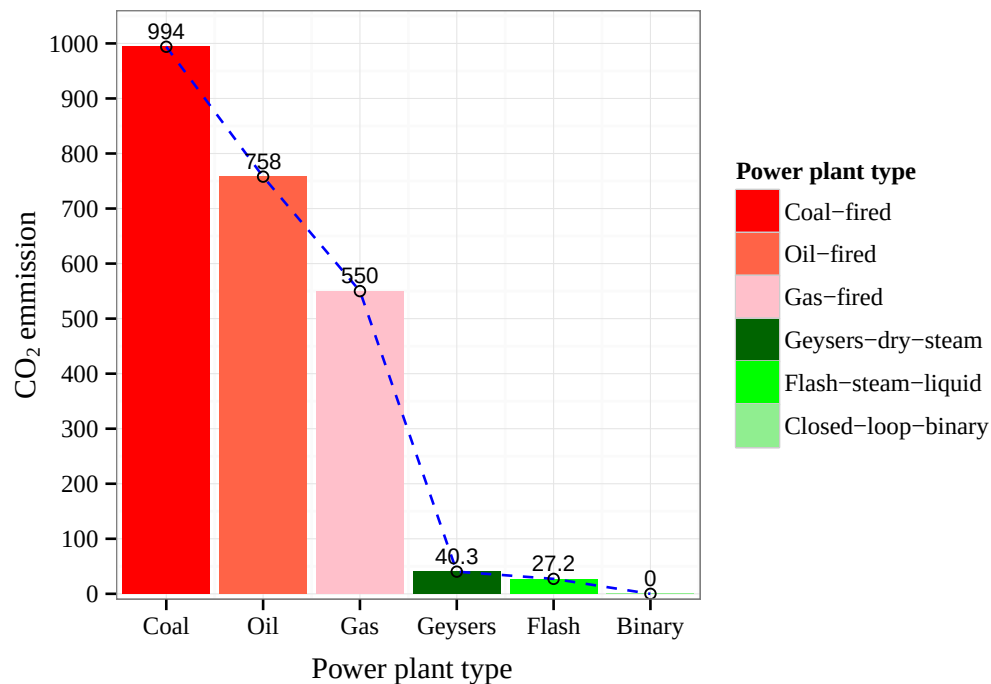


Fig. 1.1 The CO₂ emissions of geothermal power production in comparison to that of coal, oil, and natural gas. Data retrieved from (EGS, 2006, Chapter 8, table 8.1).

after the oil crisis in 1973. The development of nuclear energy proceeded as a semi-domestic form of energy. Nuclear power generated more than a quarter of Japan's electricity over the past few decades (Hamasaki, 2014). Nuclear was expected to play a major role in achieving energy self-sufficiency and carbon mitigation targets by increasing the availability factor to about 90% and building 14 new nuclear power stations. However, the Great East Japan Earthquake and Tsunami occurred on March 11th, 2011 and its induced Fukushima disaster eroded people's confidence in nuclear that it has become an unacceptable option (Vivoda, 2012). All of Japan's nuclear plants were forced to stop operation on May 5th, 2012 according to one scenario. After the earthquake and Fukushima Dai-ichi Nuclear Power Station accident, the Japanese government has to review energy and environmental policy. Japanese energy and environmental policies will shift from nuclear to renewable energy. Geothermal energy may be the most promising one.

Table 1.2 The CO₂ emissions of geothermal power production in comparison to that of coal, oil, and natural gas. Data retrieved from (EGS, 2006, Chapter 8, table 8.1).

Resource type	Plant type	CO ₂ kg/MWh	SO ₂ kg/MWh	NO _x kg/MWh	Particulates kg/MWh
Fuel resources (Firethermal)	Coal-fired	994	4.71	1.955	1.012
	Oil-fired	758	5.44	1.814	N.A.
	Gas-fired	550	0.0998	1.343	0.0635
Geothermal resources (Hydrothermal)	Flash-steam-liquid	27.2	0.1588	0	0
	Geysers-dry-steam	40.3	9.8e-05	0.000458	negligible
	Closed-loop-binary	0	0	0	negligible

1.1.2 Merits of geothermal energy

Renewable energy plays an important role in mitigating climate change, against global warming and ensuring self-sufficiency of energy supply (Kubota et al., 2013). Geothermal, solar, wind and biomass are typical renewable energy resources. Among these options, geothermal power generation has the advantage of providing a stable energy supply and energy security, and is also unaffected by weather conditions, in contrast to solar and wind power generation. Additionally, geothermal resources are characterized by small CO₂ emissions during power generation, vast reserves in the shallow crust, and much higher capacity utilization ratios (over 70%) than other energy resources. The use of Geothermal energy is summarized in Fig. 1.2

In addition to the use of high temperature geothermal resources for power generation, low temperature geothermal activity has been exploited for space heating, agriculture and industrial heating processes (Barbier, 2002). It is reported by the [International Geothermal Association \(IGA\)](#) that there are 10,715 megawatts (MW) of geothermal power in 24 countries, generating 67,246 GWh of electricity in 2010, which represents a 20% increase in geothermal power capacity since 2005. [IGA](#) projects that the growth will increase to 18,500 MW by 2015 (Bertani, 2012). On the other hand, direct use of geothermal energy is one of the oldest, most versatile and also the most common form of utilization of geothermal energy (Dickson et al., 1988). It dates back thousands of years, when people began using hot springs for bathing, cooking food. In modern direct use systems, a well is drilled into a geothermal reservoir to provide a steady

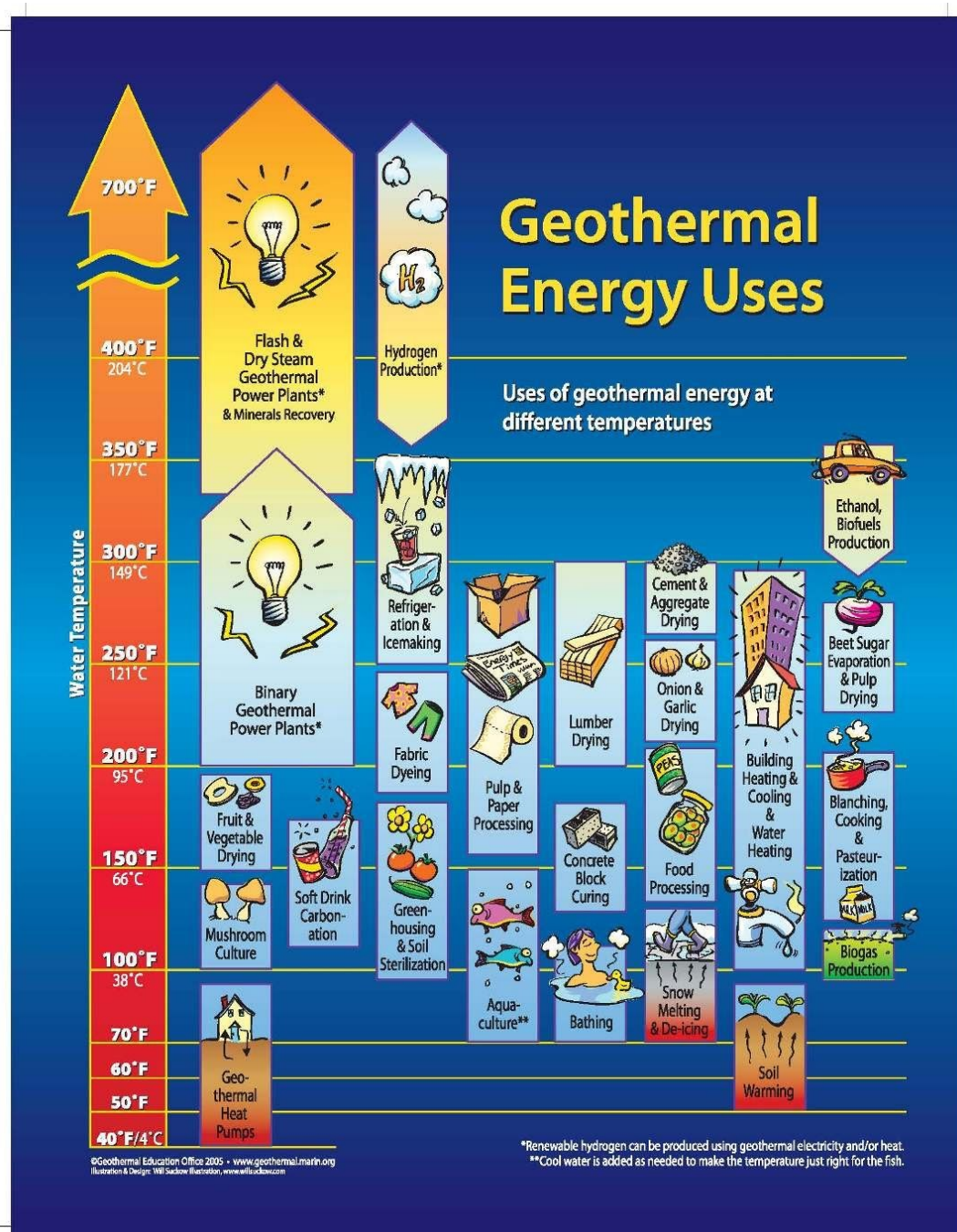


Fig. 1.2 The usage of geothermal energy at different temperatures and depths ^a.

^aThis figure downloaded from <http://www.groundzerosoftware.net/Geo-energy-uses>

Table 1.3 The advantages and disadvantages of geothermal energy

Advantages	Contribute to humanity	Disadvantages
Renewable source of energy No air emissions and pollution High capacity factor (70%) Massive potential (2TW worldwide) No fuel required (Mining) Stable output regardless weather Direct use for small houses Maintenance cost is very less Smallest land footprints	Solutions for climate change Reduce greenhouse effect Constant and sustainable power Safe and Off-nuclear power Reduce reliance on fossil fuels Mitigate urban heat island Hot spring and tourism	Sites are very location-specific High upfront costs (Drilling) High installation cost Water intensive Groundwater environment issue Danger of eruption of volcano May release harmful, poisonous gases Visual pollution by pipe systems
Green, Clean, Sustainable Renewable, Environment friendly	Solutions for climate change? Against Global Warming?	High investment cost and risk Localized supply

stream of hot water. The current uses include heating buildings, raising plants in greenhouses, drying crops, heating water at fish farms, and several industrial processes, such as pasteurizing milk. The other way of direct use of geothermal resource is [Geothermal Heat Pumps \(GHP\)](#), which is a central heating and/or cooling system that transfers heat to or from the ground ^{*1}. [GHP](#) does not emit any heat to outside atmosphere as traditional air conditioners, so it is very effective for reducing urban island heat phenomenon which is a serious problem especially in mega cities. The advantages and disadvantages of geothermal are summarized in Table 1.3.

1.1.3 Geothermal resource in Japan

Japan is part of the “Pacific ring of fire” (Fig. 1.3), one of the world’s most tectonically active counties located on plate interaction zones. It contains more than 450 Quaternary volcanoes, 110 of which are currently active. As a result, Japan has abundant geothermal resources, ranking as the world’s third richest ^{*2} country in geothermal energy and the eighth highest geothermal electrical power capacity in the world (Bertani, 2012) (aslo see Table 1.1). These resources could amount to as many as 23,470,000 kW in electricity, which was estimated from a volume

^{*1}<http://www.renewableenergyworld.com/rea/tech/geothermal-energy/geodirectuse>

^{*2}http://www.japanfs.org/en/news/archives/news_id035043.html

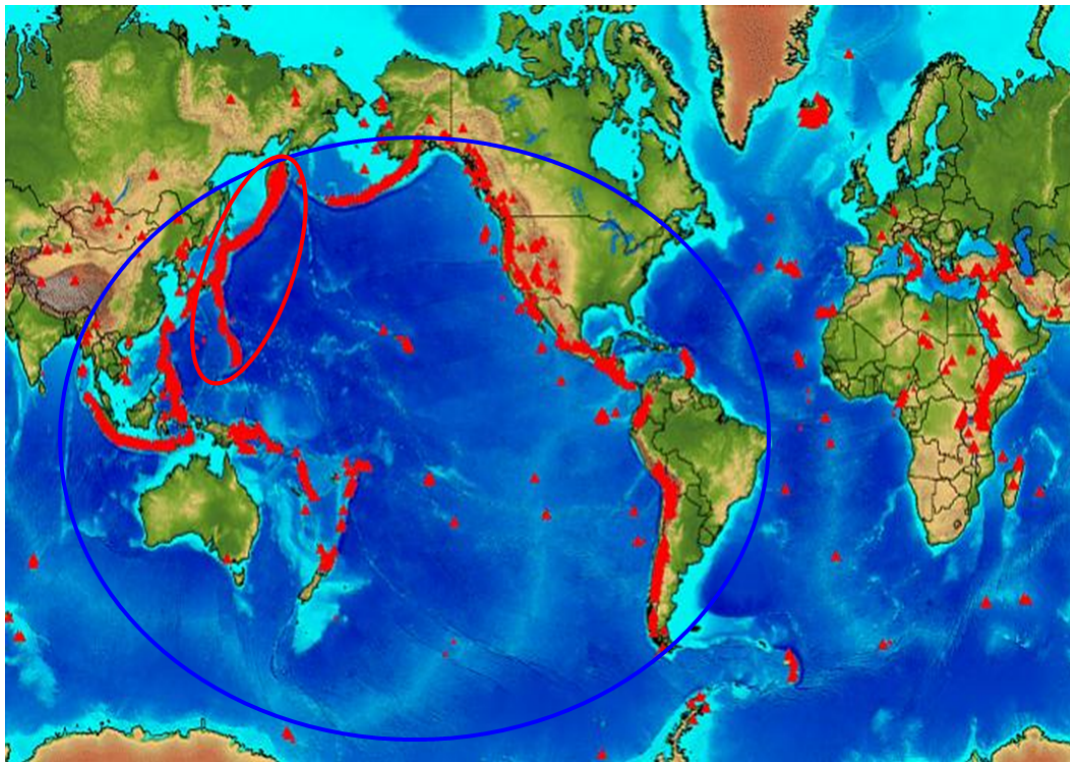


Fig. 1.3 The Pacific ring of fire, red triangles represent volcanoes.

of geothermal water laying up to a depth of 3 km and its temperature is more than 200 °C (New Energy and Industrial Technology Development Organization (NEDO), 1994), equivalent to the energy consumed by 40 million ordinary households. Yet only two percent of it is actually used for power generation. As a result, the development room of geothermal energy utilization in Japan is significantly large ^{*2}. Direct use of geothermal energy in Japan has mainly been for bathing, other uses include space heating, agriculture, snow melting, etc. GHP in Japan has been used for space heating and cooling in most part of Japan ^{*3}.

Geothermal power development in Japan

The first experimental geothermal power generation in Japan took place in 1925 at Beppu, Oita prefecture, in southern Japan. The capacity of the first experimental geothermal power generation was 1.12 kWe. The first and second geothermal power plants in Japan began their

^{*3}<http://grsj.gr.jp/en/geothermalinJ/index.html>

operation in 1966 and 1967 at Matsukawa and Otake, respectively. There are currently 21 electric power units in Japan at 18 geothermal sites, mainly in Northern Honshu and Kyushu islands. After the first oil shock in 1973, the Sunshine project was initiated by the Ministry of Economy, Trade and Industry. Since then four more power plants in 1970s, three plants in 1980s, and six plants plus two units in 1990s were opened. However, in the late 1990s, the government reduced geothermal budgets dramatically. No new projects of more than 10 Mw have been developed since 1996. Figure 1.4 shows the capacity and power production of geothermal power plants in Japan from 1967 to 2009. Surveys for new power plants were restarted recently since Japan's nuclear disaster has hurt the credit worthiness of the electric utilities sector. Especially the open of Waita geothermal power plant, which located in a region famed for its natural hot springs and volcanic activity in Kumamoto prefecture on the southern island of Kyushu, Japan's first new geothermal power plant in 15 years, herald the start of a new chapter in Japan's energy industry.

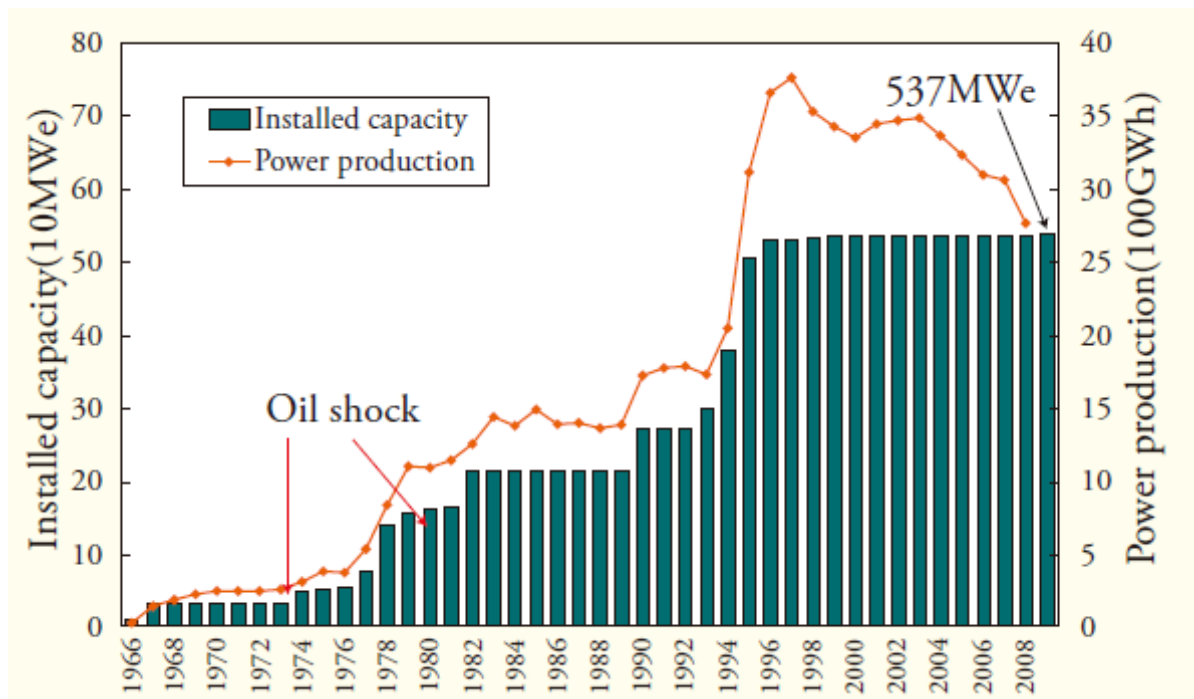


Fig. 1.4 Capacity and power production of geothermal power plants in Japan (1967 to 2009)^a.

^a<http://geothermal.jogmec.go.jp/history/history.html>

Geothermal direct use in Japan

In comparison with electricity production from geothermal energy, direct utilization has several advantages, such as much higher energy efficiency, generally the development time is much shorter, and normally much less capital investment is involved. Additionally, direct application can use both high- and low-temperature geothermal resources. In Japan, direct use of medium- and low-enthalpy geothermal water is dominant in the areas around the high-enthalpy geothermal areas, where hot springs resources are also abundant, while use of ground heat in shallow layers is nationwide. The capacity of facilities using ground heat is merely 1% of all direct use. Larger part of direct use of geothermal energy has been for bathing in Japan. Other uses include greenhouse heating, fish breeding, industrial process heat, space heating, hot water supply and swimming pool, snow melting and air conditioning (cooling), ground heat uses (eg. [GHP](#)), etc. Although [GHP](#) market is still small in Japan, they are applied to a variety of buildings, such as public facilities (museum, schools, etc.), offices, hotels and individual houses. [GHP](#) is very effective for reducing [Urban Heat Island \(UHI\)](#) phenomenon which is a serious problem especially in mega cities like Tokyo because [GHP](#) does not emit any heat to outside atmosphere.

1.2 Problem statement and motivation

Geothermal energy, as natural steam and hot water, is considered to be a clean and renewable natural resource. However, to be considered economically viable, the cost of extracting and using this energy must be less than the value of that energy in the market it is being delivered to. The key element in the assessment of geothermal energy systems is the resource type. Moeck (2014) proposed a classification scheme for geothermal resources based on the idea of “geothermal play types”, which involves convective-dominated geothermal plays and conductive-dominated geothermal plays. Conduction and convection are two ways that transfer the heat from the Earth’s interior to the surface. Convection is a vastly more efficient process of heat

transfer than conduction (Barbier, 2002). The majority of the geothermal resources currently exploited for power generation are convective hydrothermal systems that are found in regions associated with tectonic plate boundaries and volcanic areas (all the power plants in Japan are this type). These systems have high temperatures at shallow depths ($<3,000$ m), due to high heat flows caused by hot fluids moving upwards through rocks with high natural permeability. Hence, convection has been of particular interest for geothermal energy exploitation, because it has the potential to transport heat to relatively shallow depths and to replenish the supply of hot water as it is extracted (Barbier, 2002). Thus, identification of convective-dominated areas can help explore economically viable geothermal energy. Chapter 4 aims to identify the two types of heat transfer from a set of temperature-logging data sets.

Although geothermal energy in Japan is in huge quantities, it is unevenly distributed and often at depths too great to be exploited. Data obtained from wells (i.e. Drill cuttings, cores, and logs) are the most reliable and direct one for characterizing the thermal, geochemical and geological structures of geothermal systems (Asaue et al., 2006; Teng et al., 2007). In situ drilling borehole data provide the most accurate information in the exploration process. 3D modeling of subsurface temperature using limited borehole data is useful for visualizing subsurface temperature distribution and hence is helpful in geothermal resources exploitation, since the temperature degree and depth of geothermal resources decide the method of their utilization (plant or direct use). Kriging has been proved to be a suitable interpolation method (Agemar et al., 2012). Of all the kriging types, I choose [Kriging with External Drift or trend \(KED\)](#), which makes it possible to accommodate a trend in data which is essential for the estimation of subsurface temperatures. Although drilling data provides accurate information in the exploration process, it is the mostly costly exploration method and hence the number and depth of the wells tend to be limited and they also tend to be irregularly distributed throughout the study area. Active geothermal fields have natural manifestations and temperature anomalies at the ground surface, such as volcanoes, hot springs, mud pots and fumaroles, which are natural

indicators of geothermal activity that can provide a visible sign of the transport of heat and mass through the crust. At a preliminary stage of geothermal exploration, remote sensing, geologic mapping, geophysics, geothermics, geochemistry, drill target selection, well logging and geostatistics interpretation are carried out in and around these surface manifestations.

On the basis of this consideration, [Thermal Infrared Remote sensing \(TIR\)](#) which is an efficient technique for obtaining the [Land Surface Temperature \(LST\)](#) has great potential to contribute positively to cost-effective geothermal energy evaluation and exploration. [LST](#) anomaly is a key indicator of geothermal areas. The application of [TIR](#) for detecting and quantifying [LST](#) anomalies have been successfully used in geothermal fields since 1960s (Hodder, 1970; Meer et al., 2014; Qin et al., 2011; Urai, 2002). Recently, [TIR](#) was applied to detection of hot springs using thermal infrared data from [Advanced Spaceborne Thermal Emission and Reflection radiometer \(ASTER\)](#) and [Airborne Visible/Infrared Imaging Spectrometer \(AVIRIS\)](#) (Hellman et al., 2004). Landsat band 6 imagery from [Thematic Mapper \(TM\)](#) onboard Landsat 4, 5, and [Enhanced Thematic Mapper Plus \(ETM+\)](#) sensor onboard Landsat 7 has also been widely applied for [LST](#) studies (Andres et al., 1995; Flynn et al., 2001; Harris et al., 1999; Vlassova et al., 2014; Wang et al., 2013). Sobrino et al. (2004) compared three methods of retrieving [LST](#) from band 6 imagery. The latest Landsat 8 launched in February 2013 ensures the continuous use of Landsat series imagery for [LST](#) retrieval (Jiménez-muñoz et al., 2014; Yu et al., 2014). In this study, the Landsat 8 [Thermal InfraRed Sensor \(TIRS\)](#) band 10 imagery was used for the [LST](#) analysis. Understanding the surface energy balance and underground heat transfer will contribute to identification of geothermal resource areas in the study area as well as in other regions worldwide.

A combination of [Three Dimension \(3D\)](#) modeling of [Subsurface Temperature \(SST\)](#) using datasets composed of well-logging temperature and [LST](#) is essential to comprehensive understanding of geothermal systems and resource exploration. Accordingly, Chapter 5 aims

to present the spatial variability of geothermal energy distribution in Hokkaido, Japan, by comparison and combination of 3D modeling of well-logging temperature data with LST data derived from TIR.

Due to various geological settings, faults, volcanic zones and topographies, the geothermal systems are widely distributed under different conditions. Therefore, it is difficult to make a variogram or geostatistical modeling in the extensive area (eg. The whole Japan) for the lack in stationarity. Consequently, In Chapter 6, based on different tectonic settings (Plate, Arc, and Tectonic Line), volcanic front, fault zones and geography, I divided the Japan land into six zones of different geothermal systems: Hokkaido, Northeast of Honshu, Center of Honshu, Southwest of Honshu and Shikoku, Kyushu, Nansei Islands and Izu-Bonin geothermal systems.

Above paragraphs, I have described the problems in present geothermal exploitation technologies and proposed the main objectives in this dissertation. Figure 1.5 intuitively shows the motivation of this thesis.

1.3 Originality and contributions

This Dissertation will make several contributions to the fields of geothermal, remote sensing, R programming, data curation and reproducible researches. I proposed a combination of LST retrieved from TIRS of Landsat 8 and SST estimated by geostatistics for characterizing geothermal resource in Japan. Originality and contributions of this dissertation can be summarized by the following eight points.

- In addition to the traditional 3D temperature modeling only using well-logging data, I proposed a method of combining TIR retrieved LST and SST by well-logging.
- An idea of residual LST by subtracting the scene average of multi-season images was proposed. By the residual LST, good correspondence between the thermal anomalies

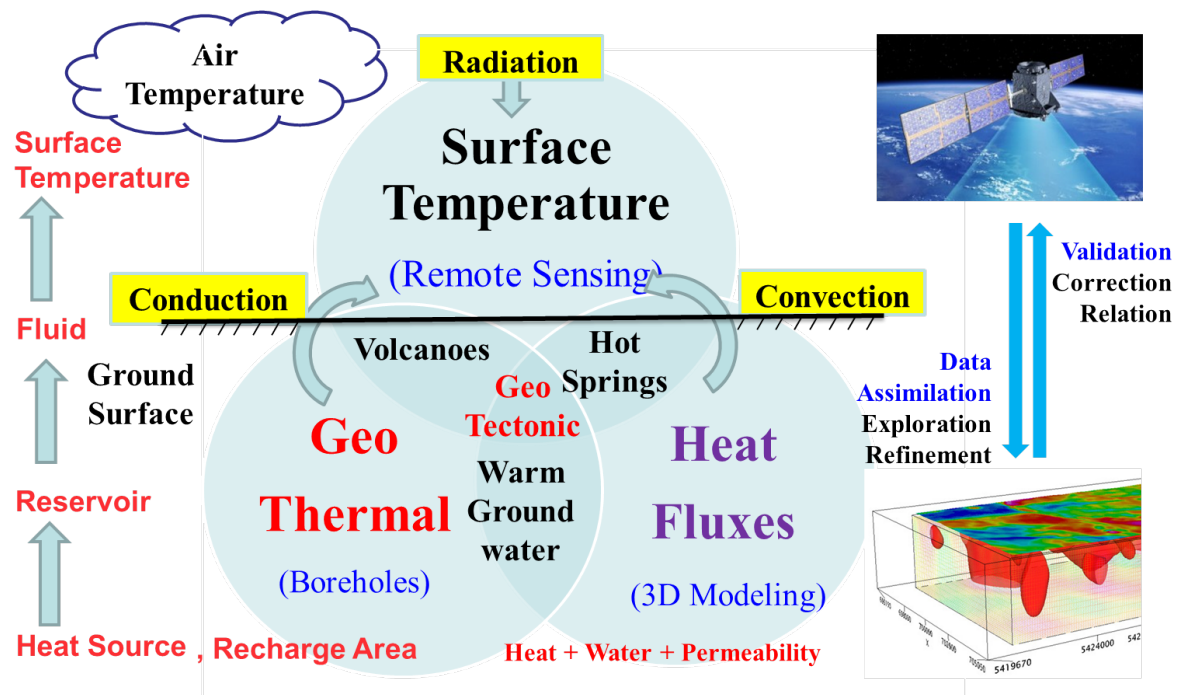


Fig. 1.5 The motivation and concept of the thesis.

and geological elements such as volcanoes, hot springs, and faults was revealed and the high geothermal potential zones was detected.

- Identification of the two types of heat transfer is of significance to improve the accuracy of 3D temperature modeling and prediction of deeper temperature. I also proposed a new method and index to identify conductive or convective heat transfer type underground.
- A 3D variogram for SST estimation over the wide study area was constructed and remarkable features could be detected in the 3D SST model by KED method.
- Two R packages TIR and GeothermaR were developed to analyze TIR imagery and assess geothermal resources.
- The latest Landsat 8 satellite was launched in February 2013 and therefore there are few researches done about its performance, specially in its applications related to geothermal assessments. Accordingly, this research present one of the first results of retrieving LST using its new upgrades at TIR bands.

- The results proved the effectiveness of the combination of [LST](#) and [SST](#) using [TIR](#) and geostatistical spatial modeling to explore high potential zones of geothermal resource over a wide area.
- Finally, I conducted this research following the reproducible research ideas which I would like to contributed to, such as, use free and open software (Linux, R, QGIS etc.), avoid mouse click and use command line tools and use programming source scripts as much as I can. Consequently, a large dataset is made available for reproductive research, and any person who are interested in my thesis can reproduce the results, figures, even all dissertation anywhere as desired.

Based on these important ideas and results, my originality must be high and the method proposed can be widely used to various purpose including wide-area geothermal resource assessment and exploration world widely.

1.4 Structure of dissertation

This dissertation is the results of geothermal resource assessment in shallow crust of Japan by a new method that combines three-dimensional temperature modeling using well-logging dataset and [LST](#) mapping using [TIR](#) imagery. It is composed of seven chapters.

Chapter 1: introduces this PhD research by describing the background and motivations.

Geothermal energy, one of renewable energy, plays an important role in reducing carbon-dioxide emission and ensuring self-sufficiency of energy supply because of its huge amount of resource. Another meriy is stable energy supply regardless weather conditions as compared to solar and wind power generation. For enhancement of the use and development of geothermal resource, accurate assessment of geothermal system including geological structure, fluid flow, and [SST](#) from the near surface down to great depths is indispensable. In addition, detailed mapping [LST](#) is effective to detect geothermal

manifestations on the ground from extensive areas. Based on these background, this research is aimed to develop the methods for estimating [SST](#) and [LST](#), characterize the temperature distributions, and integrate [SST](#) and [LST](#) for geothermal resource assessment.

Chapter 2: describes the details of main methods used for estimating [SST](#) and [LST](#) including remote sensing, [Geographic Information System \(GIS\)](#), geostatistics, and their related R packages. Among many algorithm of [LST](#) retrieval using [TIR](#), a method using only one parameter (emissivity of surface material) was clarified to be the most suitable because this research used many low cloud cover scenes with different seasons. At first, temperature at top of atmosphere is calculated using the Planck's law and then, it is corrected by considering the [LST](#). As for [SST](#), [KED](#) is the best because temperature data are not statistically stationary and increase with depth, which expressed as a trend. For simplification, a global linear trend related to the physics of conduction was adopted for the log-transformed temperature data used for [KED](#) estimation. The principles of [LST](#) retrieval algorithm using thermal infrared remote sensing were well presented. Also, principles on the geostatistics modeling were described in detail.

Chapter 3: summarizes the prototype of data and its integration by remote sensing, [GIS](#), and geostatistics. For this integration, a [Coordinate Reference Systems \(CRS\)](#) of Japan was developed. Next, details of all dataset used in this research, which are well-logging temperature data, [TIR](#) data from Landsat 8 and [MODerate resolution Imaging Spectroradiometer \(MODIS\)](#), and geothermal manifestation data such as location of active volcanoes, and [Land-Use and Land-Cover \(LULC\)](#) map based on a classification of [Advanced Land Observing Satellite \(ALOS\)](#) images are described.

Chapter 4: proposed a method to identify two thermal types of heat transfer, conduction and convection, in the crust from the temperature-logging dataset. This identification is essential to geothermal exploration and reservoir mapping because it is related to geothermal fluids and convective zones have preferable energy potential with higher

temperatures at shallow depths. This identification was accomplished by a statistical-based method and coefficient of determination of 0.9 was revealed to be a proper threshold to discriminate the two types.

Chapter 5: describes an application of the proposed methods to Hokkaido island and the results. A set of the 28,476 well-logging temperature datapoints collected from 433 sites and 13 Landsat 8 **TIRS** images were used to clarify the extensive variability of temperatures in the upper crust and on the surface over Hokkaido in northern Japan. The **SST** model was constructed using the dataset and a geostatistical method, **KED** while the **LST** map was first produced using the universal algorithm examined in Chapter 2, and then transformed into the residual form by subtracting the scene average temperature to detect local thermal anomalies. **3D SST** was calculated for depths of 100 m to 1500 m and a unit grid size of 1000 m by 1000 m and 100 m in the horizontal and vertical directions, respectively. Remarkable features were detected from the **SST** model by **KED**; specifically, high temperature zones were mostly located in the western region and a part of the eastern region in accordance with the distribution of Quaternary volcanoes and high heat flow, while the central region was dominated by low temperatures due to the thick cover of sedimentary rocks. Although **LST** is mostly controlled by **LULC**, such as urban areas and topography, high temperature anomaly zones were detected in the high **SST** areas. These findings demonstrate the effectiveness of the combination of subsurface and surface temperatures using geostatistical spatial modeling and **TIR** for identification of zones with high potential for geothermal resources.

Chapter 6: extends the analysis of Chapter 5 to whole Japan island using the 85,545 well-logging temperature datapoints collected from 1,125 sites. From the result of **SST**, the high temperature zones are appeared in eastern Hokkaido, northeast Honshu, middle of Honshu, and southern Kyushu, in particular, northeast Honshu region is characterized by the most concentration of the high temperature zones. These distributions are concordant

with the active and Quaternary volcanoes. There are high temperature zones unrelated to the volcanoes such as the southern top of Kii peninsula. Latent magma can be estimated under this peninsula associate with the subduction of the Philippine Sea Plate. Using the SST, heat energy can be calculated over Japan, which implies high recourse potential in the northern and southern Tohoku and middle Honshu regions. LST obtained by the set of MODIS scenery also reveals the high potentials of these regions.

Chapter 7: summarizes the main results of each chapter, contribution of the results to geothermal science and technology, and future significant works.

1.5 Summary

This chapter aimed to introduce the background, motivation and structure of this dissertation. The background was first introduced from the need and merits of geothermal energy in Japan, then, geothermal resources in Japan was reviewed in terms of geothermal power develop and direct use. Japan has large development room of geothermal energy utilization. However, how to exploit such energy is a big challenge. Under this context, I brought out the advanced technologies (eg. 3D modeling, remote sensing) that are proper way for geothermal exploration. The problem of each technology were pointed out and then the motivation of this dissertation were proposed. Then, the originality and contributions of this dissertation were introduced. Finally, the structure of this dissertation were listed.

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Chapter 2

Methods for Surface and Subsurface Temperature Estimation

“By three methods we may learn wisdom: First, by reflection, which is noblest; Second, by imitation, which is easiest; and third by experience, which is the bitterest.”

Confucius, *teacher, editor, politician, and philosopher*

“A picture can tell a thousand words, but a few words can change its story.”

Sebastyne Young, *Wait Until You're Old and Alone (2010)*

In this chapter, three methods [TIR](#), [GIS](#) and Geostatistics, and their related R packages are introduced respectively. The principle of each technology is introduced. LST retrieval algorithms are illustrated. The detail of geostatistics are depicted. These methods are well applied in Chapter [5](#) and [6](#).

2.1 Thermal Infrared Remote Sensing

Remote Sensing (RS) is specifically useful in the previous step of geothermal exploration because the acquisition of information using multiple bands (Fig. 2.1) and cover wide area from remote satellite or air board sensors in contrast to on site investigation (Fan et al., 2010; Tian and Koike, 2014; Tian, Wang, Koike, et al., 2010). The application of **RS** in geothermal resource exploration and research are summarized in Fig 2.2 (Abrams et al., 2013; Hellman et al., 2004; Hodder, 1970; Koike et al., 2001; Kratt, Calvin, et al., 2010; Kratt, Coolbaugh, et al., 2009; Littlefield et al., 2009; Meer et al., 2014; Mia et al., 2014; Pickles et al., 2001; Qin et al., 2011; Reath et al., 2013). In this dissertation, I focused on using **TIR** (see red block flow

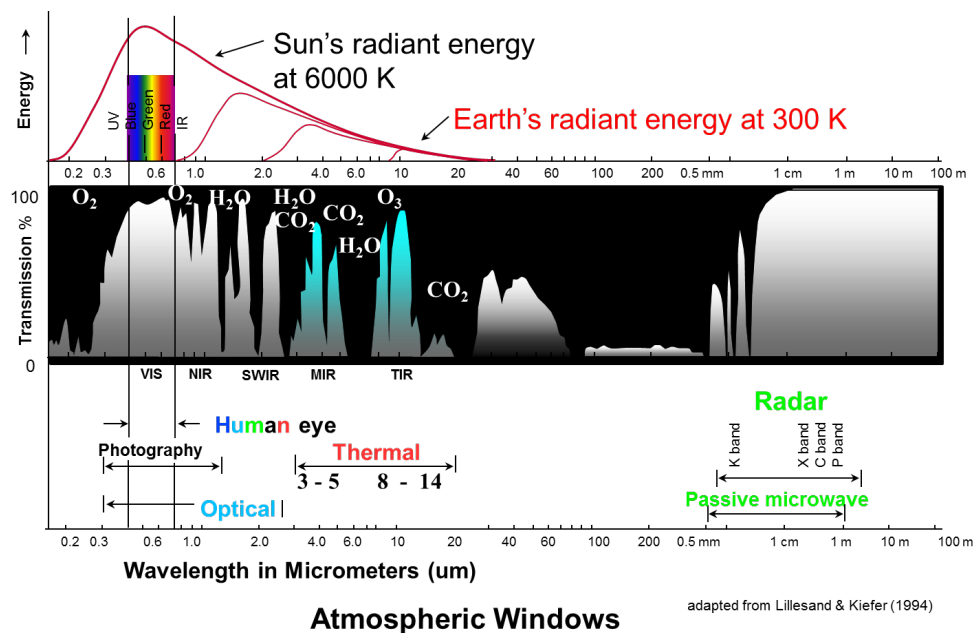


Fig. 2.1 Atmosphere window of remote sensing.

in Fig. 2.2) to detect geothermal anomalies because surface manifestations such as volcanoes, magma, hot springs, geysers, fumaroles, mineral pools etc., can be used to identify geothermal systems. These manifestations are shown in Fig. 2.3 which can be easily detected by both field surveys and also **TIR** (Tian, Wang, Kashiwaya, et al., 2015). **TIR** has been successfully applied

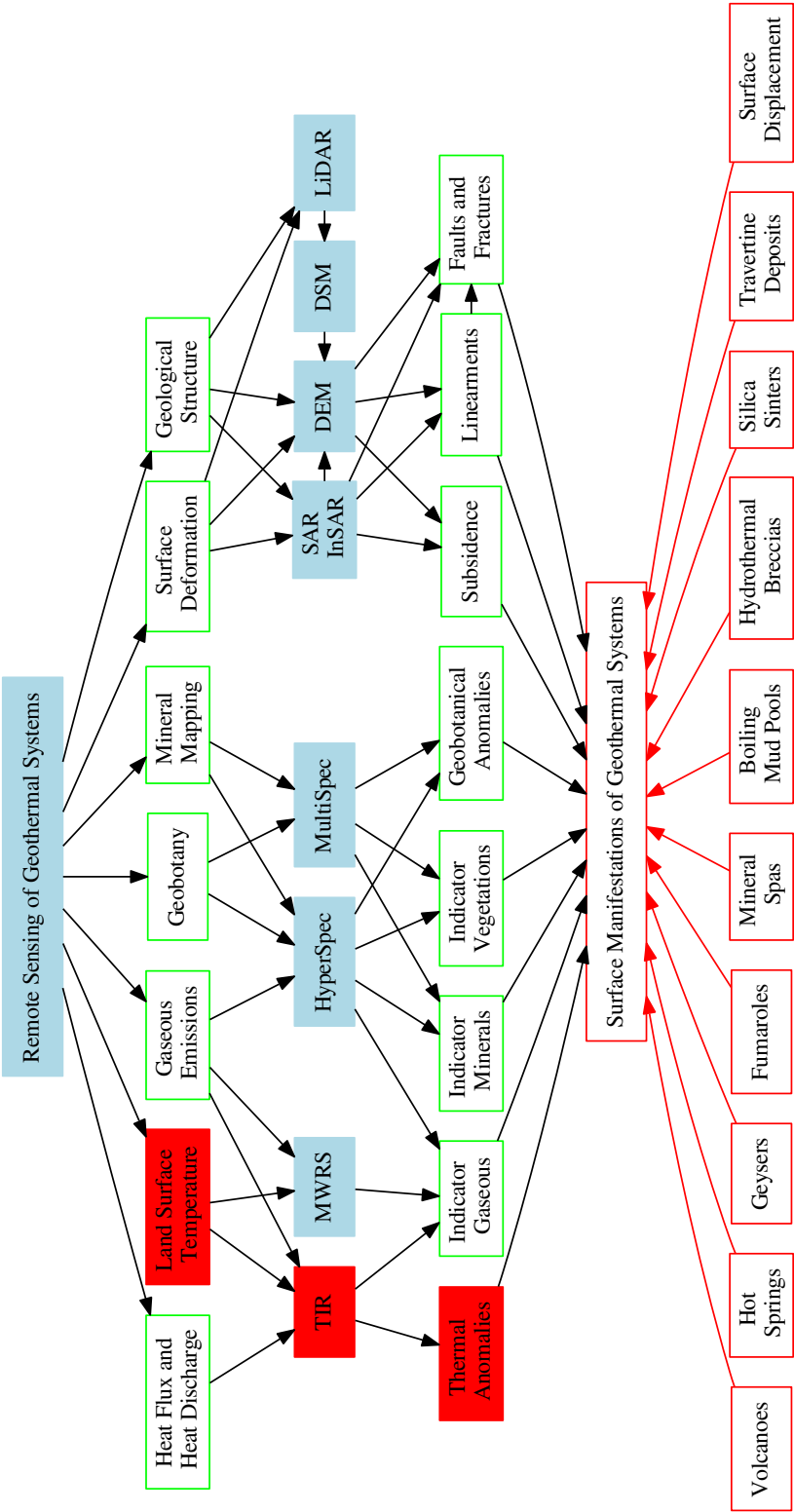


Fig. 2.2 Remote sensing of geothermal.



Fig. 2.3 Surface manifestations can be detected by remote sensing, from top left to low right are fumarole, hot spring, volcano, mud mineral pool, geysers, and magma.

to detection and quantification of **LST** anomalies and heat discharges in geothermal fields since the 1960s (see literature review in Section 1.1).

2.1.1 Physical basis of LST

According to Planck's law, spectral radiance $B(\lambda, T)$ ($\text{Wm}^2\mu\text{m}^{-1}\text{sr}^{-1}$) of black body is function of wavelength λ (m) of electromagnetic waves and temperature T (K) that can be defined as follows:

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \quad (2.1.1)$$

where h is Planck's constant (6.6256×10^{-34} Js), c is the velocity of electromagnetic waves (2.9979×10^8 m/s), and k is the Boltzmann constant (1.38×10^{-23} J/K). This equation can be simplified to:

$$B(\lambda, T) = \frac{c_1 \lambda^{-5}}{\pi(\exp(c_2/\lambda T) - 1)} \quad (2.1.2)$$

where c_1 and c_2 are the spectral constants with $c_1 = 2\pi hc^2 = 3.7418 \times 10^{-16}$ Wm^{-2} and $c_2 = hck^{-1} = 1.4393 \times 10^{-2}$ mK. The bright temperature T_B (K) can be calculated by the

$B(\lambda, T)$ of the surface material measured by a thermal sensor and using Eq. 2.1.3 as follows:

$$T_B = \frac{c_2}{\lambda \ln[c_1 / \pi \lambda^5 B(\lambda, T_B) + 1]} \quad (2.1.3)$$

2.1.2 LST retrieval algorithms

Many algorithms based on different assumptions have been proposed for estimation of LST from satellite TIR image data (Li, 2012; Li et al., 2013). For this investigation, an algorithm proposed by Artis et al (Artis et al., 1982) was selected because it requires only one parameter (emissivity of surface material), which was suitable here because LST residuals from many low cloud cover scenes with different seasons were used. The method used to obtain the LST map from the Landsat 8 TIRS band 10 image data using a set of R (R Core Team et al., 2014) scripts is summarized in Fig. 5.6. First, Digital Number (DN) was converted to $B(\lambda, T)$, which is the at-sensor spectral radiance at the middle wavelength of band 10 ($\lambda = 10.9\mu\text{m}$). T_B at sensor or Top of Atmosphere (TOA) was then calculated using Eq. 2.1.3. Next, T_B was corrected by considering the Land Surface Emissivity (LSE), ϵ . The values of ϵ were assigned to each pixel based on the categories shown in the LULC map (Fig. 5.5). Finally, LST was calculated from T_B and ϵ (Table 5.2) using following equation (Artis et al., 1982):

$$LST = \frac{T_B}{1 + (\lambda \times T_B / c_2) \times \ln \epsilon} \quad (2.1.4)$$

2.2 GIS and Geostatistics

Geographic Information System (GIS) is a computer system designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data. The basic and most important functions of GIS are mapping and spatial analysis. Geostatistics is a branch of statistics framework for data analysis, estimation, and simulation in spatial and spatial temporal data which show erratic spatial variability and spatial continuity imparted by the natural and anthropogenic processes (ASTM, 2010; Oliver et al., 2014). Nowadays, there are many GIS and statistical software implementing geostatistical methods. In this thesis, GIS and geostatistics was used as tools for describing spatial continuity, predicting values at unmeasured locations and making 3D SST temperature modeling and geothermal resource distributions. An open source statistical programming environment called R was used for all calculations. The universal steps of geostatistics analysis are summarized in Fig. 2.4. For a random process $\{Z(\mathbf{s}) : \mathbf{s} \in D\}$ the general geostatistical model is:

$$Z(\mathbf{s}) = \mu(\mathbf{s}; \beta) + \varepsilon(\mathbf{s}) \quad (2.2.1)$$

where μ is an constant mean, β is prior knowledge, $\varepsilon(\mathbf{s})$ is residual.

2.2.1 Mapping distribution of spatial dataset: using GIS

Less point pairs mean less representative, so sufficient and well distributed sample points are required to do a proper kriging interpolation. Delaunay triangulation, Voronoi map, x-y scatter plot, and pattern analysis in GIS are very useful to analyze stationarity and spatial variability of geostatistical data.

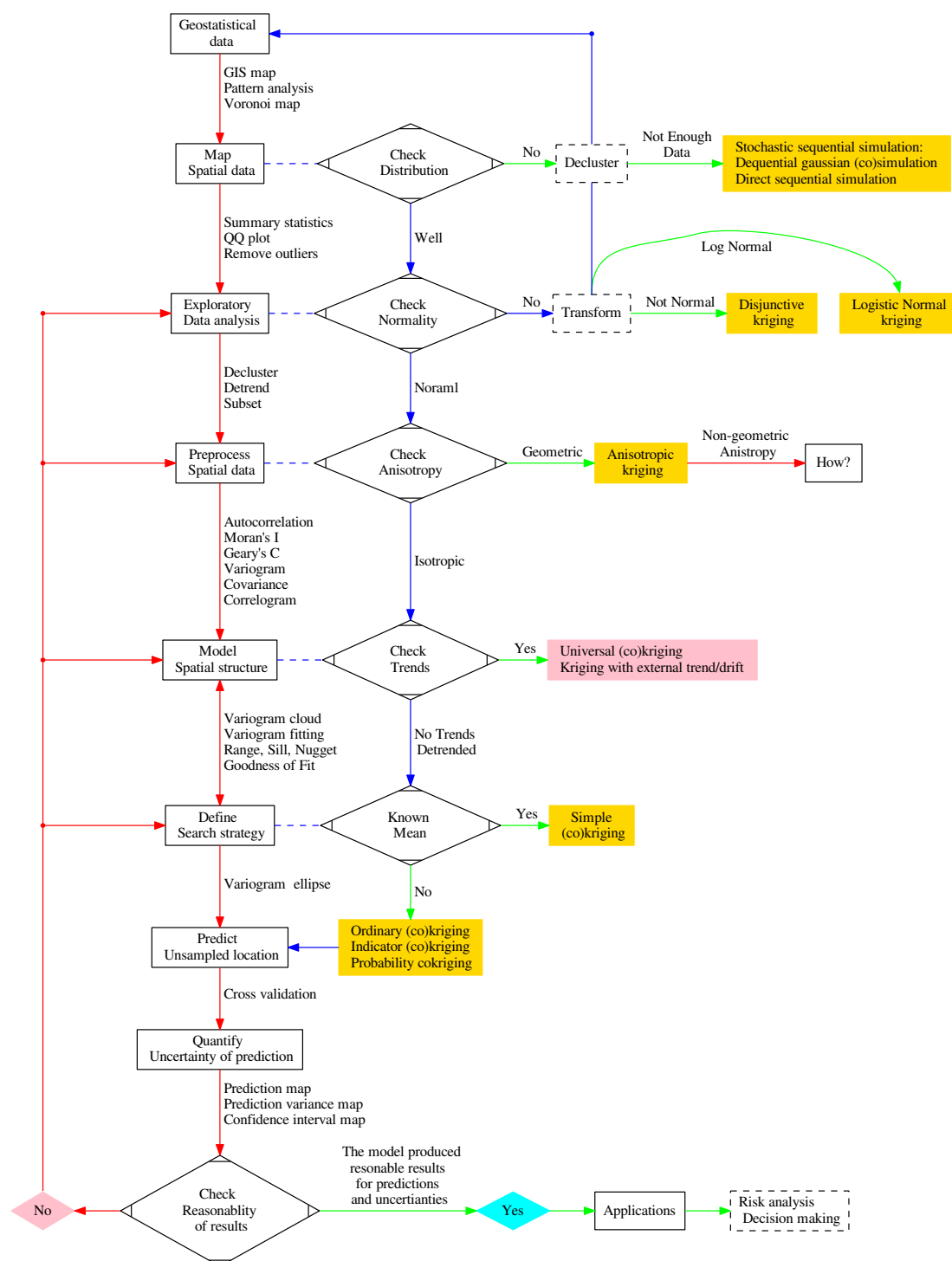


Fig. 2.4 Universal steps of geostatistics analysis and kriging estimation with GIS.

2.2.2 Exploratory data analysis: check normality

“Exploratory Data Analysis (EDA) is an attitude, a state of flexibility, a willingness to look for those things that we believe are not there, as well as those we believe might be there” (Jones, 1987). Tables, five-number summary statistics, histogram, Pareto chart, box-and-whisker plot, stem-and-leaf plot, scatterplot matrix, normal qqplot, trend analysis, regression analysis, Principal Component Analysis (PCA) etc. are basic tools for EDA and Initial Data Analysis (IDA). IDA is a part of EDA which focuses more narrowly on checking assumptions required for model fitting and hypothesis testing, and handling missing values and making transformations of variables as needed. These tools are widely applied in detecting and describing normality, patterns, trends, and relations in geostatistical data.

2.2.3 Pre-process spatial data: check continuity

There are some basic assumptions for kriging estimation in stationarity which all statistical properties at the moments (mean, variance) of the joint density are invariant, in other words it depend only on the relative locations of attribute values:

1. **Random function:** is the assumption that the dataset comes from non-random sample of one realization of a random function (this is essentially a non-testable assumption).
2. **Intrinsic stationary:** is the assumption that the dataset comes from a random process with a constant mean and a semivariogram that depends **only** on the distance and direction separating any two locations. The random function is assumed to be at least intrinsic stationary in kriging estimation.
3. **Second order stationarity:** is the assumption that the dataset comes from random process with a constant mean, and spatial covariance that depends **only** on the distance and direction separating any two locations. (Second order stationarity implies intrinsic

stationarity but the reverse is not implied, and in many cases of kriging, it is desirable for the random function to be second order stationary).

Anisotropy

1. **Isotropy:** means that the semivariance depends only on the distance between points, not direction. (one circle-like shape variogram ellipse in [Two Dimension \(2D\)](#) or ellipsoid in [3D](#), same sill and range).
2. **Geometry Anisotropy:** means the semivariance depends on the distance as well as direction between points. Geometric anisotropy has variations for distance h in one direction being the same as variations for distance $k \times h$ in another direction (Burrough, [1986](#)). (one variogram ellipse in [2D](#) or ellipsoid in [3D](#), same sill but different range).
3. **Non-Geometry Anisotropy:** also called zone or local anisotropy, means the semivariance depends on the distance as well as direction between points, (multiple and specific variogram ellipse in [2D](#) or ellipsoid in [3D](#) for every node, different sill (or scale) and range in each model. To my knowledge, approximating of zonal anisotropy is not included in any common used geostatistical software).

Autocorrelation: spatial dependency

Method, tools, and indices for exploration of autocorrelation, spatial dependency, or spatial continuity in different scales including mean polish or median polish, h-scatterplots, variogram cloud, sample semivariogram (Eq. [2.2.2](#)), Sample autocovariance (Eq. [2.2.3](#)), Moran I (Eq. [2.2.4](#)), Geary C (Eq. [2.2.5](#)), Ripley K, General G et al. The traditional sample semivariogram $\hat{\gamma}$ suggested by Matheron ([1971](#)) is:

$$\hat{\gamma}(\mathbf{v}) = \frac{1}{2N(\mathbf{v})} \sum_{N(\mathbf{v})} (Z(\mathbf{s}_i) - Z(\mathbf{s}_j))^2. \quad (2.2.2)$$

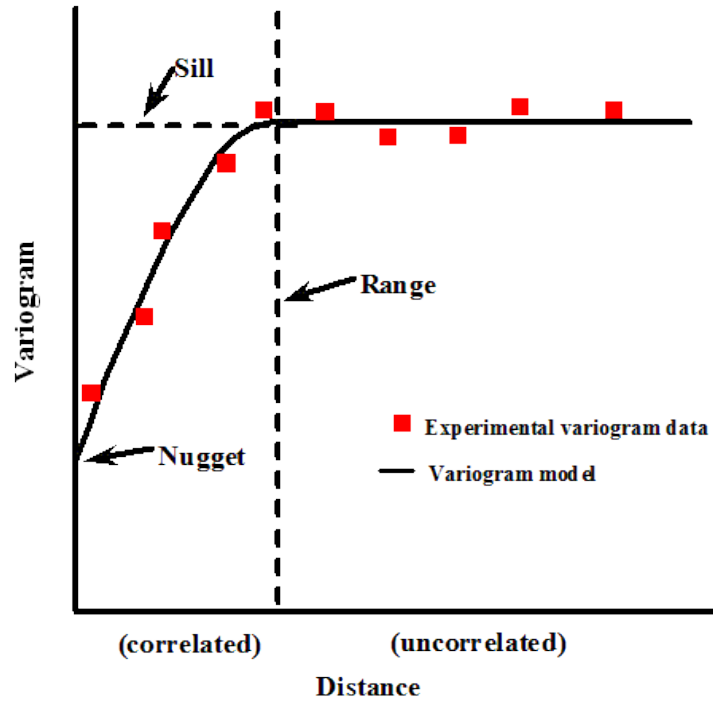


Fig. 2.5 An example of variogram ^{*1}.

where $\hat{\gamma}(\mathbf{v})$ is sample semivariogram, Z is the variable of interest, $N(\mathbf{v})$ is the number of data pairs, $\mathbf{s}_i$ and $\mathbf{s}_j$ are sample locations separated by $\mathbf{v}$. Similar to sample semivariogram, sample autocovariance is formulated as:

$$\hat{C}(\mathbf{v}) = \frac{1}{N(\mathbf{v})} \sum_{N(\mathbf{v})} (Z(\mathbf{s}_i) - \bar{Z})(Z(\mathbf{s}_j) - \bar{Z}) \quad (2.2.3)$$

where $\hat{C}(\mathbf{v})$ is sample autocovariance, Z is the variable of interest, $\bar{Z}$ is the sample mean, $N(\mathbf{v})$ is the number of data pairs, $\mathbf{s}_i$ and $\mathbf{s}_j$ are sample locations separated by $\mathbf{v}$.

$$I = \frac{n}{S_0} \frac{\sum_i \sum_j W_{ij} (Z_i - \bar{Z})(Z_j - \bar{Z})}{\sum_i (Z_i - \bar{Z})^2} \quad (2.2.4)$$

where I is Moran's I developed by Patrick Alfred Pierce Moran to measure spatial autocorrelation, n is the number of spatial points indexed by i and j , Z is the variable of interest, $\bar{Z}$ is the

^{*1}http://vsp.pnnl.gov/help/Vsample/Kriging_Variogram.htm

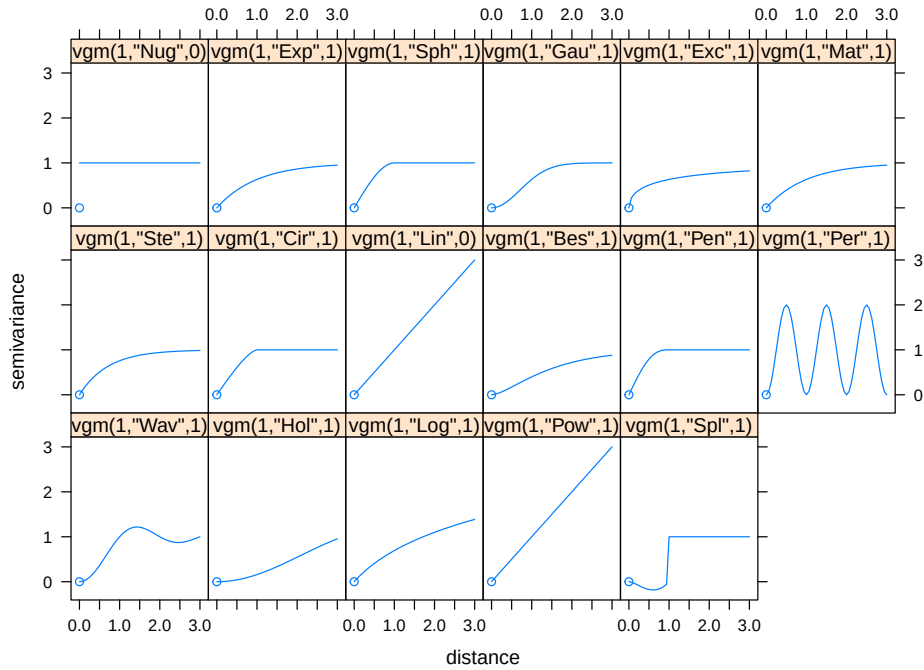


Fig. 2.6 A list of variogram models in gstat package (gstat::show.vgms).

mean of Z , and W_{ij} is an element of a matrix of spatial weights, S_0 is the sum of all W_{ij} . The value of Moran's I lies between -1 (indicating perfect dispersion of negative correlation) and 1 (perfect correlation of positive relations), while a zero value indicates a random spatial pattern. Moran's I is a measure of global spatial autocorrelation, but Geary's C is more sensitive to local contiguity.

$$C = \frac{n-1}{S_0} \frac{\sum_i \sum_j W_{ij} (Z_i - \bar{Z})(Z_j - \bar{Z})}{\sum_i (Z_i - \bar{Z})^2} \quad (2.2.5)$$

where C is Geary's C also known as Geary's contiguity ratio or the Geary index developed by Roy C. Geary, n is the number of spatial points indexed by i and j , Z is the variable of interest, $\bar{Z}$ is the mean of Z , and W_{ij} is an element of a matrix of spatial weights, S_0 is $\sum_{ij} (W_{ij}) \times 2$. Geary's C is inversely related to Moran's I , but it is not identical. The value of Geary's C lies between 0 and 2. One means **no** spatial autocorrelation. Values < 1 demonstrate increasing positive spatial autocorrelation, while values > 1 illustrate increasing negative spatial autocorrelation.

2.2.4 Define search strategy: variogram selecting

Normally, at the very beginning, the search radius includes the correlated area (the variogram ellipsoid ranges) because from sill value (the point where data is no longer correlated as a function of distance) every sample will be equivalent. However, sometimes with this range, the structures that appear in the final estimation do not make much sense, and if worse, the image could be with artifacts-concentric shape perhaps due to a failure in the smoothness. It's better to correct this by increasing the number of search points or artificially increase the ranges of the variogram. As for 3D data (boreholes, drills, well-logging, etc.), it's better to increase the horizontal search and decrease the vertical one because vertically correlation drops quickly.

2.2.5 Predict unsampled location: using kriging

Unlike straightforward point interpolation methods, such as nearest point, splines, trend surface, moving average or moving surface, Kriging is a family of estimators used to interpolate spatial and spatial-temporal data with Best Linear Unbiased Estimator (B.L.U.E) based on a statistical method. This family includes Simple Kriging (SK), Ordinary Kriging (OK), Universal Kriging (UK), Indicator Kriging (IK), Co-Kriging (CK) and others. The choice of which kriging to use depends on the characteristics of the data and the type of spatial model desired. Different kriging types have different assumptions and analytical goals (Fig. 2.4):

Simple Kriging: assumes a known mean $\mu(s) = c$. However usually is not the case of natural environment.

Ordinary Kriging: assumes a constant unknown mean (mean needs to be estimated). OK is most widely used kriging method.

Universal Kriging: assumes a trend in the data, It is used to estimate spatial means when the data have a strong trend and the trend can be modeled by simple functions.

Indicator kriging: uses indicator (0 or 1) variables to generate probabilities that a critical value was exceeded or not at each location in the study area.

Co-kriging: is an extension of kriging which enables the use of observed values of two variables.

2.2.6 Application: 3D subsurface temperature modeling using KED

As shown in Fig. 5.3, the temperature data are not statistically stationary because they increase with depth. KED (Eq. 2.2.6) is suitable to produce a spatial model for regionalized data with significant spatial trends (see Fig. 2.4), such as the temperature logging data used in this study. KED incorporates a local trend within the neighborhood search window as a smoothly varying function, which is usually a polynomial function of the coordinates, and then estimates the trend component within the window and a value at the unsampled point by simple kriging using the residual sample data. This residual is equal to the sample value minus the local mean in the window (Bourennane et al., 2000). KED is calculated by:

$$\hat{Z}(s_0) = \sum_{l=0}^L a_l f_l(s_0) + \sum_{i=0}^n \lambda_i (Z(s_i) - \mu(s_0)) \quad (2.2.6)$$

where, s is the coordinate in N dimension, Z is the target variable under consideration, $\hat{Z}$ is the estimated value of variable Z at an unsampled point s_0 , n is the number of sampled points used for the estimation, which is dependent upon the size of the neighborhood search window, $\sum_{l=0}^L a_l f_l(s_0)$ is a deterministic function with a known function $f_l(s_0)$ and unknown coefficients a_l , $L \ll N$. λ_i is the kriging weight, and $\mu(s_0)$ is the mean sample data within the search window. The optimal weights are obtained by solving simultaneous linear functions produced from a variogram model.

2.3 R packages for spatial data analysis

R (R Core Team et al., 2014) is the world's most popular statistical data analysis software^{*2}. There are more than 7,000 packages in R ecosystems to deal with various data form different disciplines. Table 2.1 list main R packages for spatial analysis, geostatistics, raster data analysis GIS and RS. The packages listed in the Table 2.1 are mainly from three Comprehensive R Archive Network Task Views (CTV), "Spatial", "Spatiotemporal" and "TimeSeries". A description of all R packages is beyond the scope of this dissertation. For more information please refer to the Comprehensive R Archive Network (CRAN) task views^{*3}.

Table 2.1 List of R packages related to GIS, RS and spatial analysis.

Packages	Vector analysis dominated	Raster analysis dominated
Data type	point, polyline, polygon	grid, lattice, raster
Base library	spatial, sp, rgeos	rgdal, gdalUtils, raster
Spatial data	maps, mapdata, maptools, geomapdata	raster, rworldmap, cshapes,
Climate data	BerkeleyEarth, CHCN RNCEP, crn	dataRetrieval, marmap, rnoaa, rNOMADS
Climate data	GhcnDaily, meteoForecast	raincpc, rainfreq, weatherData
Geology data	gmt, rFDSN, GSIF, soilDB	waterData
Earth Science	decctools, Metadata	cimis, FAOSTAT
Data I/O	sp, rgeos, maptools, PBSmapping	rgdal, gdalUtils, ncdf4
Projection	mapproj	rgdal, PROJ.4
GIS	RArcinfo, RpyGeo, RSAGA, geosphere	GRASS, spgrass6, plogKML, deldir
Geostatistics	gstat, geoR, geoRglm, spdep,	nlme, surveillance, plm, splm, sphet
Geostatistics	RandomFields, spBayes, Stem, spcopula	fields, vardiag, geospt, rtop, georob
Auto Interpolation	automap, intamap	
Point pattern	spatstat, stpp, stppResid, splancs,	stam, ptproc, spsurvey, lgcp
Spatial regression	Spdep, nlme, spgwr, spatcounts, lme4	McSpatial, spatialprobit
Spline and Trajectory	akima, deldir, tripack, MBA	adeHabitatLT, trip, diveMove, move

^{*2}<http://blog.revolutionanalytics.com/popularity/>

^{*3}<http://cran.r-project.org/web/views/>

Spatial temporal	spacetime, xts, SpatialTemporal	surveillance, rts, spTimer
Time series	stat, forecast, tseries, ts	zoo, svtsplot
Remote sensing		raster, RStoolbox, GRASS
Classification	classint, DClustter, kernlab	kml, kml3d, e1071, flexclust
Landsat	wrspathrow, teamlucc	landsat, rLandsat8
MODIS	MODISDownload	MODIS, MODISTools, modisccloud, rts
Mapping	maptools, PBSmapping, gmt, marmap	leafletR, RgoogleMaps, RKML
2D visualization	lattice, ggplot2, micromap	ggmap, plotKML rasterVis, osmar
3D and 2.5D Vis.	rgl, lattice, misc3d, scatter3d	plot3D, rasterVis, latticeExtra
Interactive Vis.	ggvis, rCharts, plotly, googleVis	d3Network, clickme, gg2v, cranvas

2.4 Summary

This chapter focused on the introduction of main methodologies utilized through this dissertation, including remote sensing, geographic information systems, geostatistics and their related R packages. The application of remote sensing in geothermal resource exploration and research was summarized exhaustively. Then, the physical basis of **LST** and its retrieval algorithm using thermal infrared remote sensing were described. In addition, principles on the geostatistics modeling were illustrated in detail, including mapping, normality and continuity checking, variogram selecting, prediction and **KED** modeling. Finally, a series of related R packages were introduced.

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Chapter 3

Data Collection and Integration for TIR and Geostatistics

“You can have data without information, but you cannot have information without data. The goal is to turn data into information, and information into insight.”

Daniel Keys Moran, *programmer and science fiction writer*
Carly Fiorina, *former president of Hewlett-Packard*

“Errors using inadequate data are much less than those using no data at all.”

Charles Babbage, *mathematician, philosopher, and computer scientist*

In this chapter, the prototype of data and its integration in [RS](#), [GIS](#) and geostatistics are introduced first, then the [CRS](#) used in Japan and developed for this thesis are described, finally all the dataset used in this thesis are summarized.

3.1 Introduction of data integration in remote sensing , geographical information systems and geostatistics

RS and GIS techniques have been shown to be useful for environmental monitoring and geological analysis (Ha and Koike, 2011; Ha, Koike, and Nhuan, 2013; Kennedy et al., 2009; Koide et al., 2012; Masoud et al., 2011; Tian and Koike, 2014; Tian, Wang, et al., 2011; Wang, Zhang, et al., 2014; Wang, Tian, et al., 2013). Satellite remote sensing is based on detecting the way surfaces reflect and absorb visible and infrared radiation. Remote sensors detect the radiance associated with a given pixel and then this information is often converted to the spectral reflectance. GIS are important tools for viewing broad-scale patterns of spatial data, organizing and integrating information about an area, and analyzing that data to answer questions. Geostatistics was developed by geologists to take into account variations of spatially correlated phenomena. They all aims to spatial data but have their own data format. The initial

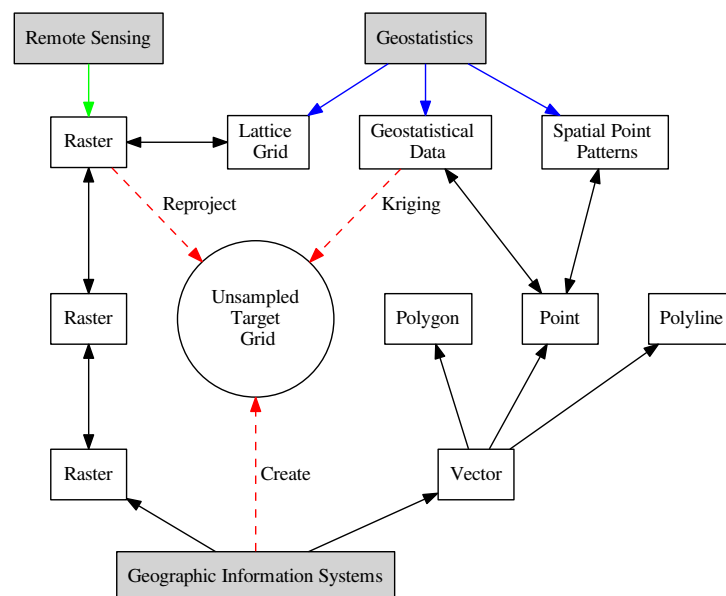


Fig. 3.1 Prototype of data intergrated in RS, GIS and geostatistics.

and important thing is to integrate the data and make them uniform format for further analysis. Figure 3.1 shows the way to integrate the data in RS, GIS and geostatistics.

3.2 Scale and coordinate reference systems

Scale refers to the spatial or temporal dimension of a phenomenon, which is undoubtedly one of the most fundamental aspects of any research. Nature phenomenon have their own distinctive scales (or ranges of scales) that characterize their behavior (e.g., typical spatial extent or event frequency). Although the concept of a scale can be applied more broadly, this dissertation is primarily about geographic scale. Scale here is used to refer both to the magnitude of a study (e.g., its geographic extent) and also to the degree of detail (e.g., its level of geographic resolution). It is used in the context of space (geographic scale) and time (temporal scale). The emergence and widespread use of geographic information technologies, including remote sensing and GIS started the development and implementation of techniques for dealing explicitly with scale. Compared to traditional paper map, GIS opened the possibility for multiscale representations, and for databases that contain digital versions of the contents of many maps at different scales (Goodchild et al., 1997).

Coordinate systems enable geographic datasets to use common locations for integration. A coordinate system is a reference system used to represent the locations of geographic features, imagery, and observations, within a common geographic framework. In a GIS, there are two common types of coordinate systems; Geographic Coordinate Reference System (GRS) and Projection Coordinate Reference System (PRS) which are referred to as map projections such as Universal Transverse Mercator (UTM), Lambert conformal conic projection (LCC), Albers Equal-Area (AEA) etc ^{*1}. A work-flow of data transformation is described in Fig. 3.2. A GRS includes an angular unit of measure, a prime meridian, and a datum (based on a spheroid). The

^{*1}<http://resources.esri.com/help/9.3/arcgisengine/dotnet/89b720a5-7339-44b0-8b58-0f5bf2843393.htm>

spheroid defines the size and shape of the earth model, while the datum connects the spheroid to the earth's surface. Datum and CRS used for Japan map and sptail data were summarized in Table 3.1 and Table 3.2 respectively.

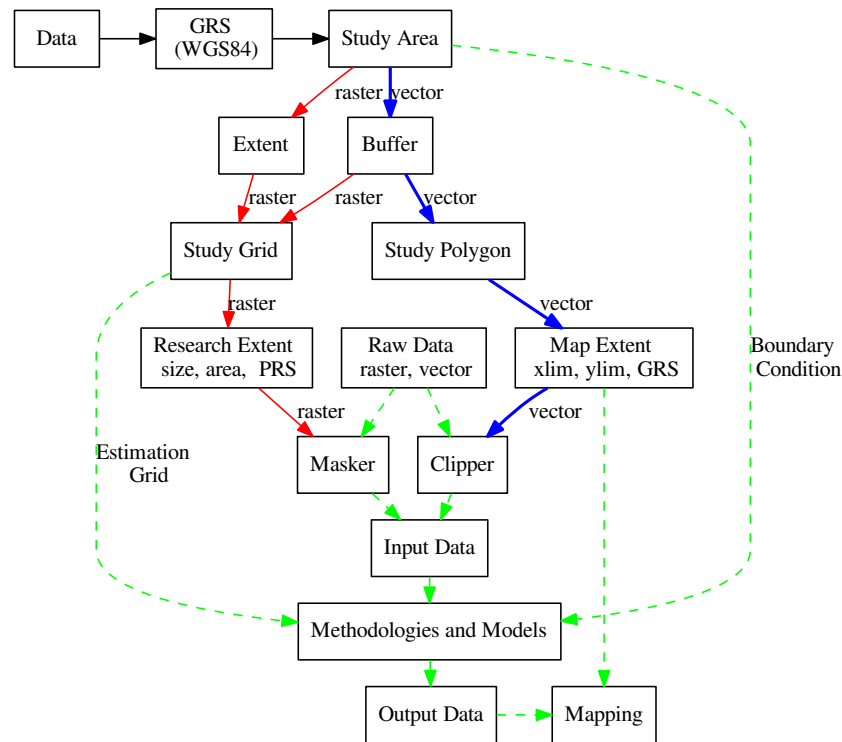


Fig. 3.2 Data processing flow map.

Table 3.1 Datum used for Japan map and sptail data

Datum EPSG	Tokyo Datum 4301	JGD2000 4612	JGD2011 6668	WGS84 4326	Sphere Mercator
Ellipsoid	Bessel 1841	GRS 1980	GRS 1980	WGS 1984	Sphere
Equatorial axis(Major)	6377397.155	6378137.0	6378137.0	6378137.0	6371000
Polar axis(Minor)	6356078.965	6356752.3141	6356752.3141	6356752.3142	6371000
Inverse flattening (1/f)	299.1528128	298.257222101	298.257222101	298.257223563	0
Coordinate	Tokyo	ITRF94	ITRF2008	WGS84	Sphere
Utilization Periods	Japan ~2002.3	Japan 2002.4~Now	Japan 2011.10~Now	GPS, World Google Earth	Google Map Open layers

Table 3.2 CRS used for Japan map and sptail data

PRS	Ellipsoid	Zone	EPSG	PROJ4 Parameters
-	Tokyo	-	4301	+proj=longlat +ellps=bessel +towgs84=-146.336,506.832,680.254,0,0,0,0 +no_defs
-	WGS84	-	4326	+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs
-	JGD2000	-	4612	+proj=longlat +ellps=GRS80 +towgs84=0,0,0,0,0,0,0 +no_defs
-	JGD2011	-	6668	+proj=longlat +ellps=GRS80 +towgs84=0,0,0,0,0,0,0 +no_defs
TM	Tokyo	1~19	30161~30179	+proj=tmerc +lat_0=36 +lon_0=139.83333333333333 +k=0.9999 +x_0=0 +y_0=0 +ellps=bessel
	Tokyo			+units=m +no_defs
TM	JGD2000	1~19	2443~2461	+proj=tmerc +lat_0=36 +lon_0=139.83333333333333 +k=0.9999 +x_0=0 +y_0=0 +ellps=GRS80
	ITRF94			+towgs84=0,0,0,0,0,0,0 +units=m +no_defs
TM	JGD2011	1~19	6669~6687	+proj=tmerc +lat_0=36 +lon_0=139.83333333333333 +k=0.9999 +x_0=0 +y_0=0 +ellps=GRS80
	ITRF08			+towgs84=0,0,0,0,0,0,0 +units=m +no_defs
UTM	Tokyo	51-55	3092~3096	+proj=utm +zone=51 +ellps=bessel +units=m +no_defs
UTM	WGS84	51-55	32651~32656	+proj=utm +zone=51 +ellps=WGS84 +datum=WGS84 +units=m +no_defs
UTM	JGD2000	51-55	3097~3101	+proj=utm +zone=51 +ellps=GRS80 +towgs84=0,0,0,0,0,0,0 +units=m +no_defs
LCC	WGS84	Japan	Developed for this thesis	+proj=lcc +lat_1=32.8 +lat_2=43.2 +lat_0=38 +lon_0=137.5 +x_0=1000000 +y_0=1000000 +datum=WGS84 +units=m +no_defs

3.3 Borehole well-logging data

All data sources used in this dissertation were summarized in Table 3.3. The present dataset of temperature logging originates from the temperatures profiles in Japan database compiled by the Japan Atomic Energy Agency (JAEA) in 2004 (JAEA (2004)). There are 1198 available well sites with 88,629 data samples. The minimum depth of Borehole is 240 m and maximum is 6310 m. However, most borehole depth are around 1000 m, where the mean, median, first quartile and third quartile is 1066 m, 1001.5 m, 660 m and 1311 m respectively (Fig. 3.3).

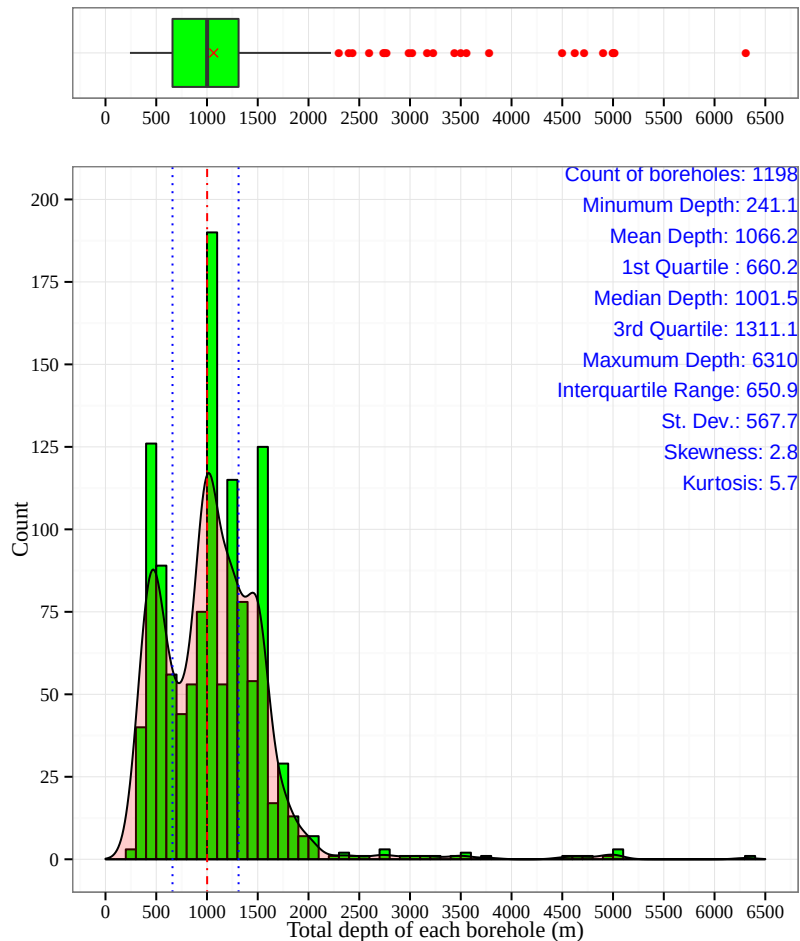


Fig. 3.3 Box-and-whisker plot and histogram of all borehole data in Japan.

Table 3.3 Data used in the thesis

Data used in the thesis	Scale	Prototype	Amounts	Source
Temperature profiles	vector	point	88629	JAEA2004
Heat flows	vector	point	3184	AIST
Thermal gradients	vector	point	1155	AIST
Active Volcanoes	vector	point	110	JMA
Quaternary Volcanoes	vector	point	455	AIST
Geothermal power plants	vector	point	22	JGEA
Hot springs	text	text	27200	JMA
Administration Map	vector	point, line, polygon	Japan	ESRI2013
Geological Map	vector	point, line, polygon	Japan	AIST
Landsat Band 10	100 m	raster	50	NASA,USGS
MODIS product	1000 m	raster	4	NASA,USGS
ASTER GED	100 m	raster		NASA,USGS
ASTER GDEM	30 m	raster		NASA,USGS
SRTM DEM	90 m	raster		NASA,USGS
LULC	30 m	raster		JAXA

3.4 Thermal infrared remote sensing imagery

3.4.1 Landsat program

The Landsat program is a joint effort of the [United States Geological Survey \(USGS\)](#) and the [National Aeronautics and Space Administration \(NASA\)](#). The Landsat family satellites have continuously acquired and delivered images of the Earth's land surface since 1972 (Irons et al., 2012). The Landsat satellites have provided a valuable archive of space-based land remotely sensed data, contributed greatly in the studies of agriculture, geology, forestry, education, region planning, mapping and global change research. Table 3.4 summarized the details of Landsat satellites in terms of launch/decommission time, operation status and the sensors on-board respectively.

3.4.2 Landsat 8

Landsat 8 satellite, also known as [Landsat Data Continuity Mission \(LDCM\)](#), launched on 11th February, 2013 by [NASA](#) and transferred operational control from [NASA](#) to [USGS](#) on

Table 3.4 Landsat remote sensing satellites family

Landsat satellite (Also know as)	Scanning method (broom)	Observation start (launched)	Observation end (decommissioned)	Orbit height (km)	Period (minutes)	Repeat cycle (days)	Swath width (km)	Crossing time (-/ + 15 m)	Main sensors ^s	Bands	Spatial resolution (Opt,Pan,TIR)	Pixel values (bits) ^p	WRS
1 (ERTS-A/1)	Whisk	1972.07.23	1978.01.06	917	103	18	170*185	9:30 am	MSS/RBV	4	80, NA, NA	6(0-63)	1
2 (ERTS-B/2)	Whisk	1975.01.22	1983.07.27	917	103	18	170*185	9:30 am	MSS/RBV	4	80, NA, NA	6(0-63)	1
3 (Landsat-C)	Whisk	1978.03.05	1983.09.07	917	103	18	170*185	9:30 am	MSS/RBV	4	80, NA, NA	6(0-63)	1
4 (Landsat-D)	Whisk	1982.07.16	1993.12.14	705	99	16	170*185	9:45 am	TM/MSS	7	30, NA,120	8(0-255)	2
5	Whisk	1984.03.01	2013.06.05	705	99	16	170*185	9:45 am	TM/MSS	7	30, NA,120	8(0-255)	2
6	Whisk	1993.10.05	1993.10.05	705	99	16	170*185	10:00 am	ETM	8	30, NA, 60	8(0-255)	2
7	Whisk	1999.04.15	Operational	705	99	16	170*185	10:00 am	ETM+	8	30, 15, 60	8(0-255)	2
8 (LCDM)	Push	2013.02.11	Operational	705	99	16	170*185	10:00 am	OLI/TIRS	11	30, 15, 100 ^p	12(0-65535)^c	2

^s Sensors: OLI = Operational Land Imager, TIRS = Thermal Infrared Sensor, ETM+ = Enhanced Thematic Mapper Plus, TM = Thematic Mapper, RBV= Return Beam Vidicon Camera.

^a NIR = Near Infrared, SWIR = Shortwave Infrared, PAN = Panchromatic, TIR = Thermal Infrared.

^b TIRS band 10 and 11 of Landsat-8 are acquired at 100 meter resolution, but are resampled to 30 meter in delivered data product. (Roy et al., 2014). ETM+ Band 6 is acquired at 60-meter resolution. Products processed after February 25, 2010 are resampled to 30-meter pixels. All bands can collect one of two gain settings (high or low) for increased radiometric sensitivity and dynamic range, while Band 6 collects both high and low gain for all scenes. Approximate scene size is 170 km north-south by 183 km east-west (106 mi by 114 mi).

^c Computers process data in increments of 8-bit bytes. Thus, 12 bits(0-4095) of data of Landsat 8 must be stored in a 16-bit integer, so the Pixel Values scaled to 0- 65,535 in product.

* The above information was adapted from from the [NASA](http://landsat.usgs.gov/about_mission_history.php) and [USGS](http://landsat.usgs.gov/about_mission_history.php) Landsat missions timeline and history web page http://landsat.usgs.gov/about_mission_history.php and http://landsat.gsfc.nasa.gov/?page_id=2281

30th May, 2013, is the latest and 7th successes of Landsat series of remote sensing satellites. Same as its predecessors, Landsat 8 runs in a sun-synchronous, near-polar orbit at an altitude of 705 km, the more details of Landsat 8 mission can be found in this recent publication by Landsat science team (Roy et al., 2014).

Compared with its predecessors Landsat 8 carries two sensors, **Operational Land Imager (OLI)** and **TIRS**. OLI is the continue of previous **Multispectral Scanner System (MSS)** on Landsat 1-3, **TM** on Landsat 4-5, and **ETM+** on Landsat 7 (Table 3.4). **TIR** was started from **TM** on Landsat 4 which have a **TIR** band 6. However **TIRS** was initially excluded from the **LDCM** requirements. The increase in applications using Landsat 5 **TM** and Landsat 7 **ETM+** thermal data in recent years, especially applications related to water resource management over agriculture areas, was a key to finally included **TIRS** as a part of Landsat 8 (Irons et al., 2012). The band properties of Landsat 8 compared to Landsat 7 were summarized in Table 3.5.

3.4.3 Access and process Landsat data

The Landsat 8 data used in this study is accessed via the *earthexplorer*^{*2} portal provided by **USGS**. Fig. 3.4 and 5.6 shows the procedures of processing the the Landsat 8 data.

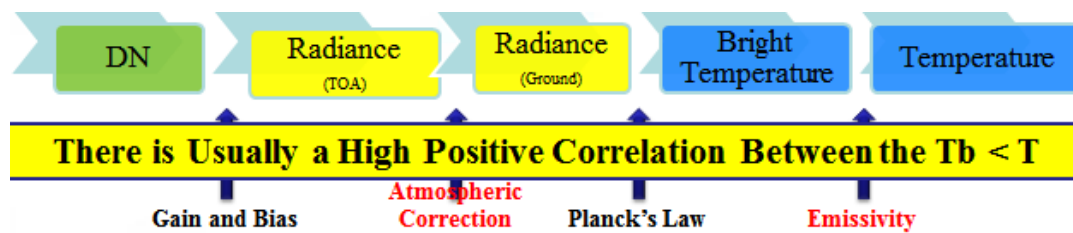


Fig. 3.4 Processing flow of the Landsat data.

^{*2}USGS EarthExplorer <http://earthexplorer.usgs.gov/>

3.4.4 Access and pre-process MODIS products

MODIS sensor on-boarded on two satellites (Terra and Aqua) are viewing the entire earth surface every 1 to 2 days with 36 spectral bands. The band width ranging from 0.4 μm to 14.4 μm , at spatial resolutions of 250, 500, and 1000 m. The **MODIS** products used in this study is accessed and processed via this R script ^{*3}. The details of **MODIS** products can be found in the list of **MODIS** products, see appendices .3.

3.5 Summary

Integration of different sources data are the initial and important step before future analysis. In our dissertation, three main spatial data types were utilized; **RS**, **GIS** and geostatistics. In this chapter, I briefly described these three data types first, and then depicted the way how to integrate them with a diagram. In addition, the concept of scale was brought out and coordinate reference systems used in Japan were introduced in detail. Finally, All data sources used in this dissertation were summarized exhaustively in terms of borehole data and **RS** data, including the sources of the data, how to access the data and some original process of the data.

^{*3}<http://r-gis.net/?q=ModisDownload>

Table 3.5 Spectral center position(λ), bandrange, bandwidth($\Delta\lambda$) and reslution of Landsat-8 and Landsat-7 bands.

Landsat-8 OLI ^s and TIRS ^s					Landsat-7 ETM+ ^s			
Bands	$\lambda(\mu\text{m})$	$\Delta\lambda(\text{nm})$	Range($\mu\text{m})$	Res(m)	Range($\mu\text{m})$	$\Delta\lambda(\text{nm})$	$\lambda(\mu\text{m})$	Bands
1 Coastal	0.443	16	0.435-0.451	30				
2 Blue	0.4825	65	0.450-0.515	30	0.441-0.514	73	0.4775	1 Blue
3 Green	0.5625	75	0.525-0.600	30	0.519-0.601	82	0.56	2 Green
4 Red	0.655	50	0.630-0.680	30	0.631-0.692	61	0.6615	3 Red
5 NIR ^a	0.865	40	0.845-0.885	30	0.772-0.898	126	0.835	4 NIR
6 SWIR ^a 1	1.61	100	1.560-1.660	30	1.547-1.749	202	1.148	5 SWIR1
7 SWIR2	2.2	200	2.100-2.300	30	2.064-2.345	281	1.2045	7 SWIR2
8 PAN ^a	0.59	180	0.500-0.680	15	0.515-0.896	381	0.7055	8 PAN
9 Cirrus	1.375	30	1.360-1.390	30				
10 TIR ^a 1	10.895	590	10.60-11.19	60 ^b (30)	10.31-12.36	2050	11.335	6 _h /6 _l ^b TIR
11 TIR2	12.005	1010	11.50-12.51	100 ^b (30)				

^s Sensors: OLI = Operational Land Imager, TIRS = Thermal Infrared Sensor, ETM+ = Enhanced Thematic Mapper Plus.

^a NIR = Near Infrared, SWIR = Shortwave Infrared, PAN = Panchromatic, TIR = Thermal Infrared.

^b TIRS band 10 and 11 of Landsat-8 are acquired at 100 meter resolution, but are resampled to 30 meter in delivered data product. The saturation temperature of both band 10 and 11 are 360 K (Irons et al., 2012). ETM+ Band 6 is acquired at 60-meter resolution. Products processed after February 25, 2010 are resampled to 30-meter pixels. All bands can collect one of two gain settings (high or low) for increased radiometric sensitivity and dynamic range, while Band 6 collects both high and low gain for all scenes. Approximate scene size is 170 km north-south by 183 km east-west. Table data adapted from: <http://landsat.gsfc.nasa.gov/?p=3186> and http://landsat.usgs.gov/band_designations_landsat_satellites.php

* Landsat 8 provides two thermal bands (bands 10 and 11) that could be used with split-window methods. However, “given the larger uncertainty in the Band 11 values, users should work with TIRS Band 10 data as a single spectral band (like Landsat 7 Enhanced Thematic Mapper Plus (ETM+)) and should not attempt a split-window correction using both TIRS Bands 10 and 11” (from http://landsat.usgs.gov/calibration_notices.php: November 14, 2013 - Upcoming change in Landsat 8 Radiometric Calibration (Revision)). Therefore in this dissertation only band 10 was used to retrieve LST.

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Chapter 4

Identification of Conduction or Convection from Temperature-logging Profiles with Application to 3D Spatial Statistics Modeling

“If we knew what it was we were doing, it would not be called research, would it?”

Albert Einstein, *scientist*

“Research is to see what everybody else has seen, and to think what nobody else has thought.”

Brian W. Kernighan, *scientist*

All the Geothermal power plant in Japan are located on a convection geothermal areas, the objective of this chapter is to find such area through interferes of borehole temperature profiles. To achieve this object, I propose a new method and R program to identify two types of heat

transfer, conduction and Convection, from borehole profiles. In addition, categorized heat transfer type map will be applied to KED to improve the estimation in Chapter 5.

4.1 Introduction of conduction and convection

As natural steam and hot water, geothermal energy is considered to be a clean and renewable natural resource. However, to be considered economically viable, the cost of extracting and using this energy must be less than the value of that energy in the market it is being delivered to. The key element in the assessment of geothermal energy systems is the resource type. Moeck proposed a classification scheme for geothermal resources based on the idea of “geothermal play types” (Fig. 4.1), which involves convective-dominated geothermal plays and conductive-dominated geothermal plays (Moeck, 2014). Conduction and convection are two ways that transfer the heat from the Earth’s interior to the surface. Convection is a vastly more efficient process of heat transfer than conduction (Barbier, 2002).

The majority of the geothermal resources currently exploited for power generation are convective hydrothermal systems (Fig. 4.2) that are found in regions associated with tectonic plate boundaries and volcanic areas (all the power plants in Japan are this type). These systems have high temperatures at shallow depths ($< 3,000$ m), due to high heat flows caused by hot fluids moving upwards through rocks with high natural permeability. Hence, convection has been of particular interest for geothermal energy exploitation, because it has the potential to transport heat to relatively shallow depths and to replenish the supply of hot water as it is extracted (Regenauer-Lieb et al., 2007). Thus, identification of convective-dominated areas can help explore economically viable geothermal energy.

In addition, the combined effects of conduction and convection cause the temperature gradient to vary laterally and vertically, which potentially not only influence the modeling of temperature

^{*1}Fig. 4.2 downloaded from EGS, Inc. <http://www.envgeo.com/Publications.html>

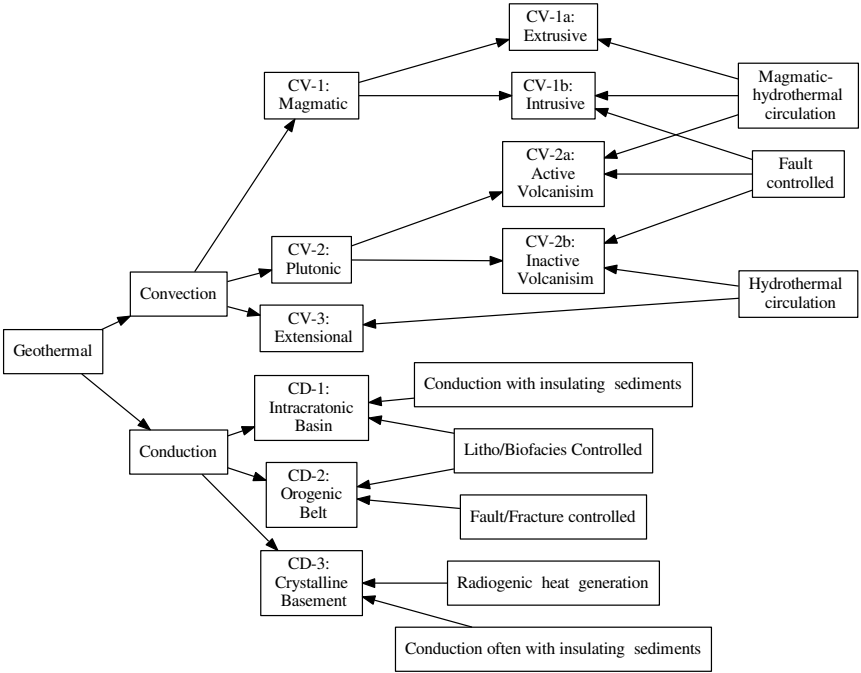


Fig. 4.1 Play types of conduction and convection (retrieved from (Moeck, 2014))

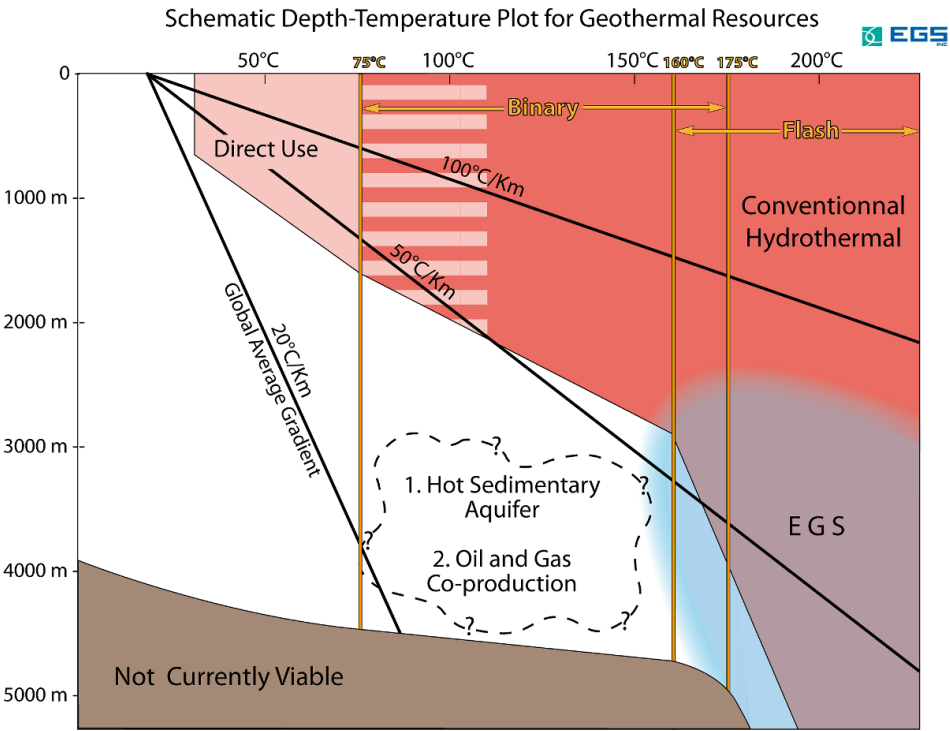


Fig. 4.2 Depth temperature plot for geothermal resource ^{*1}.

distribution but also make the temperature prediction to greater depths incorrect (Sheldon et al., 2011). Therefore, identification of the two types of heat transfer is of significance to improve the accuracy of 3D temperature modeling and prediction of deeper temperature. Moreover, the identification of conduction and convection can be used to detect geothermal reservoir because thermal conductivity in water is relatively lower than in average rock materials. Based on the above background, this chapter aims to identify the two types of heat transfer from a set of temperature-logging dataset.

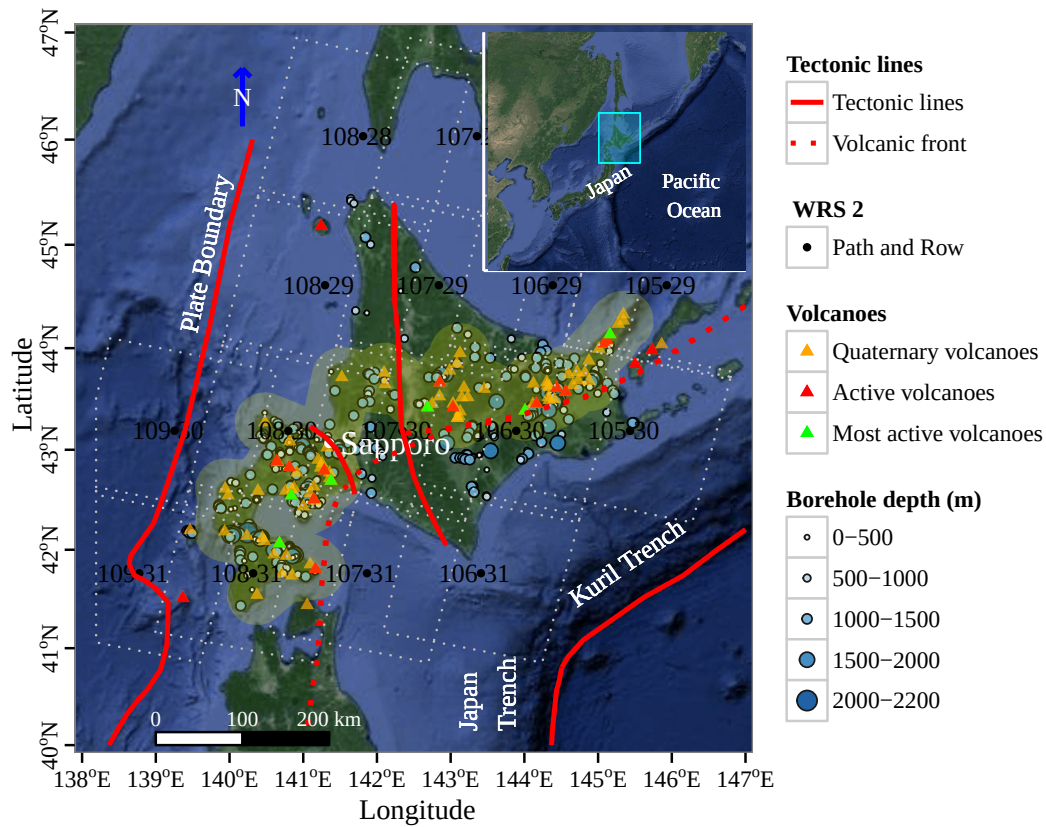


Fig. 4.3 Location of study area, Hokkaido in northern Japan, and distribution of drilling sites for temperature logging (blue circles), most active volcanoes (at least one eruption since 1900, red triangles with white crosses), active volcanoes (red triangles), quaternary volcanoes (orange triangles), trench, plate boundary and tectonic lines (red lines), volcanic front (dotted red lines). Differences in circle size denote drilling depths. Frames of Landsat series scenes used for this study (white dotted rectangles) are overlaid on the map with path and row numbers by [Worldwide Reference System-2 \(WRS2\)](#).

4.2 Study area and data preprocessing

As a case study site, I selected Hokkaido (Fig. 4.3), because of relatively much amount of borehole data (Tian et al., 2014a; Tian et al., 2014b). The subset of data below 100 m was selected to avoid seasonally change of temperature in shallow depths Fig. 4.5 shows that coefficient of determination (R^2) increased after the removing of top 100 m data from each profile. The borehole temperature profiles data source and study area details will be described in Chapter 5 Section 5.2.

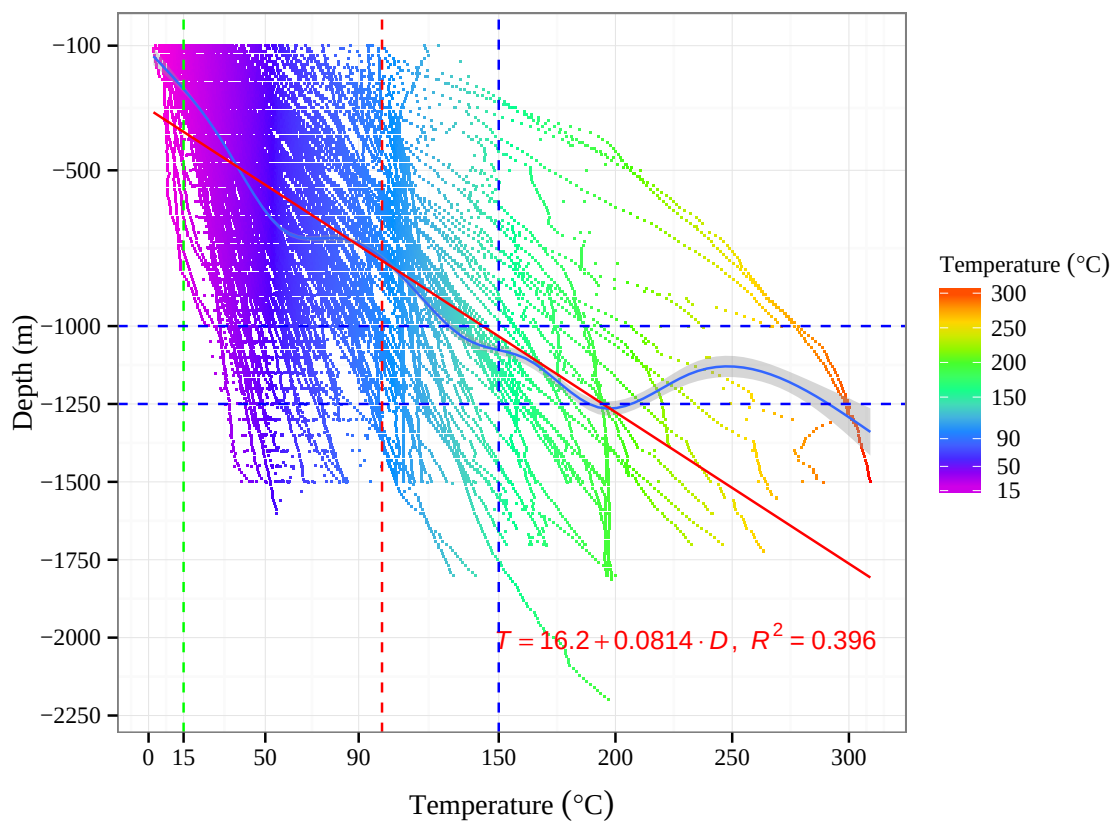


Fig. 4.4 Temperature-logging profiles with depth in Hokkaido. The red line denotes a linear regression of the relationship between temperature and depth and shows a geothermal gradient 81 °C/km. The blue line shows the non-linear regression.

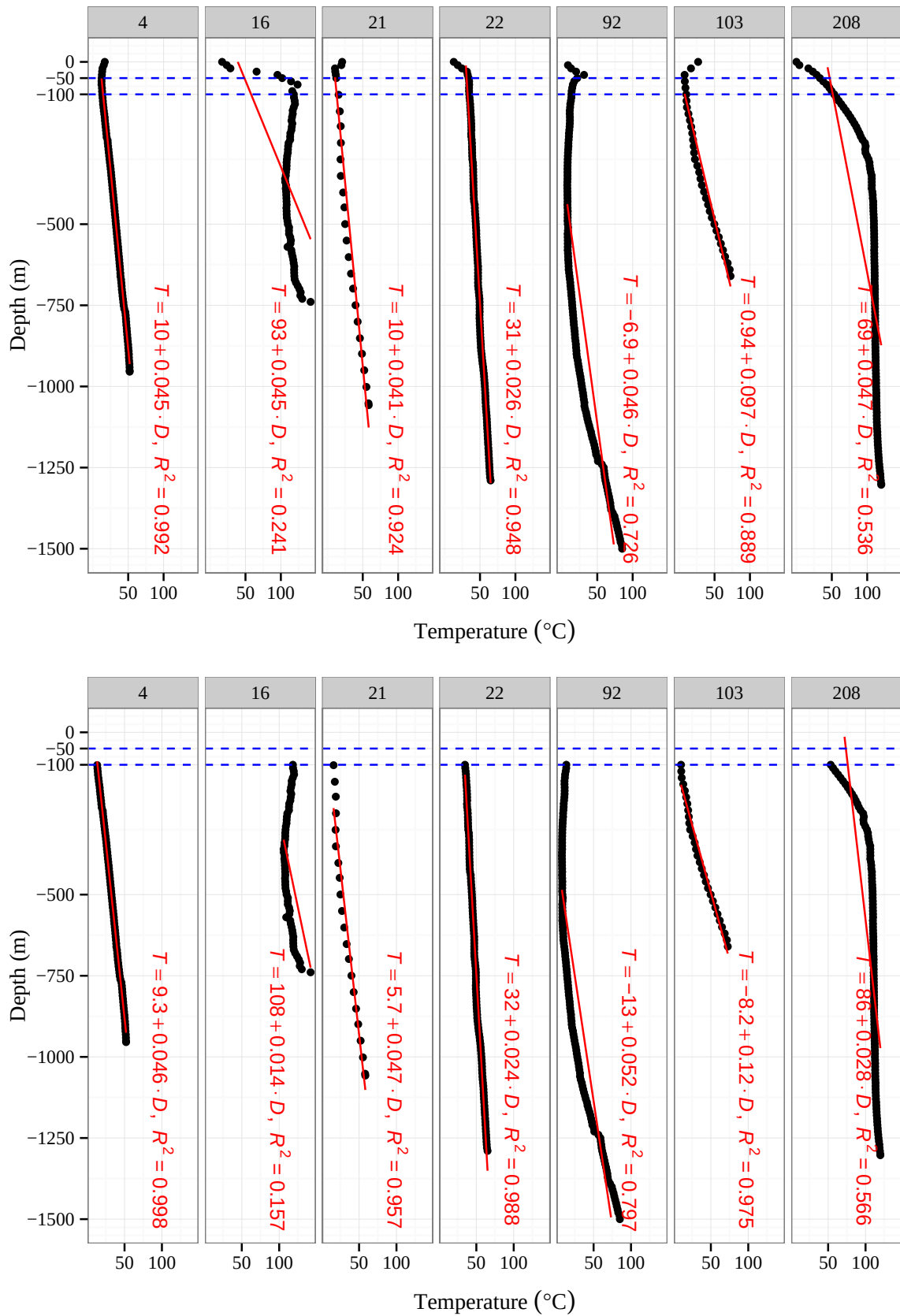


Fig. 4.5 Selected borehole profiles and their line regression to show the seasonally temperature variance (from top to bottom) and remove of the variance (from 100 m to bottom)

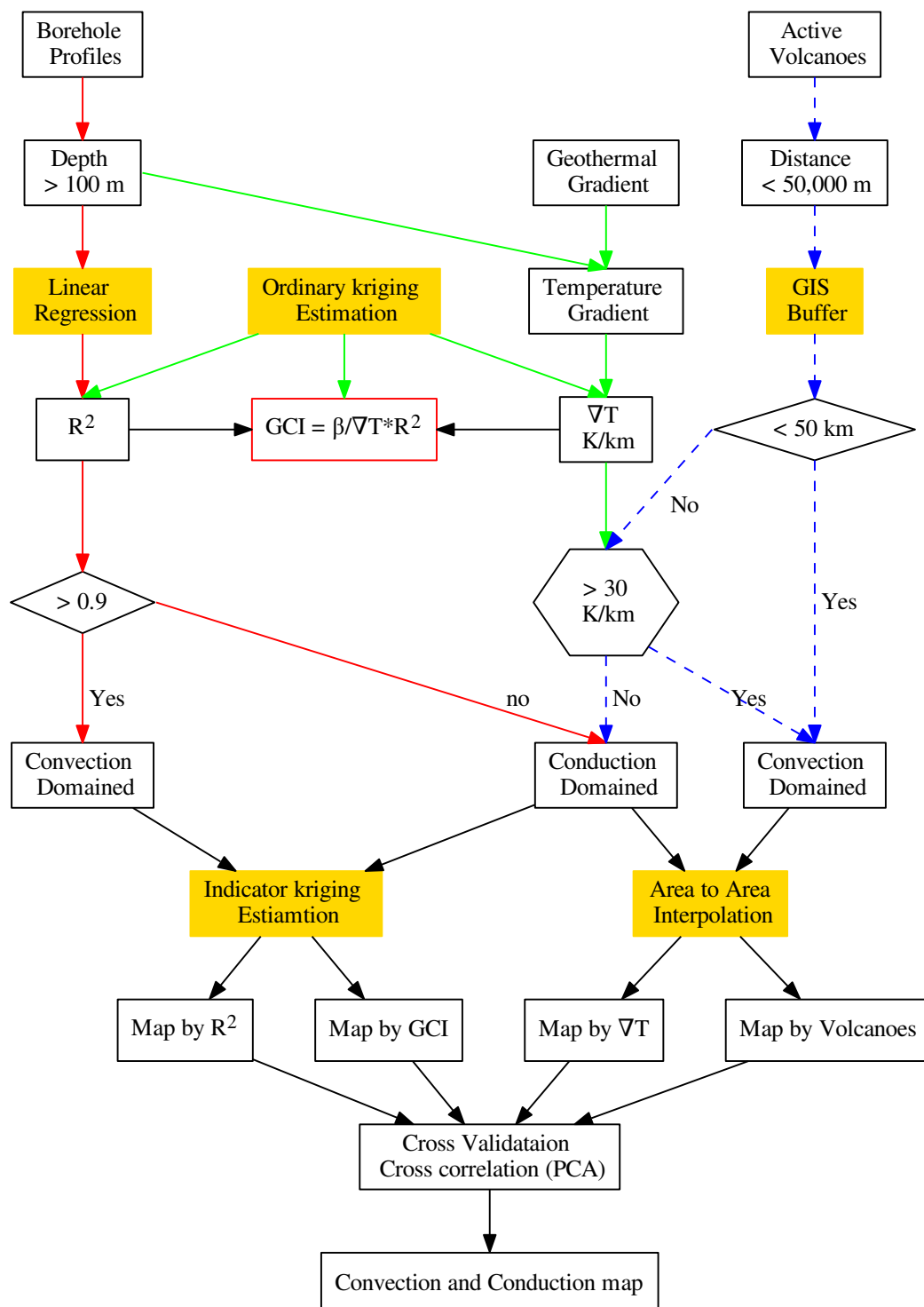


Fig. 4.6 Identification of conduction and convection areas

4.3 Methodologies

There are mainly two types of heat transfer in the Earth's crust, conductive and convective. For the main conductive type transfer, the temperature profile is approximated as a line. On the contrary, for the convection type transfer, the temperature profile draws a curve that represents a proxy for the determination of geothermal reservoirs in the area due to advection of thermal energy. The flow map of identify the two types of heat transfer is shown in Fig. 4.6.

In statistics, the better the linear regression fits the data, the closer the value of the *coefficient of determination* denoted R^2 to one. For example, if $R^2 = 0.9$, it refers that approximately ninety percent of the variation in the response can be explained by the linear fitting. Consequently, R^2 was chosen as a variable to describe the linearity of the temperature profile. I applied linear regression method to each temperature profile. Given data set has values y_i (black dot in Fig. 4.7, also called the *observed values*), each of which has an associated linear regression modelled value f_i (sometimes referred to as $\hat{y}_i$, also called the *predicted values*, the black line in the right of Fig. 4.7). In this thesis, y_i here represent to the temperatures of each borehole profile. Firstly the mean of the observed data $\bar{y}$ calculated by equation 4.3.1:

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \quad (4.3.1)$$

where $\bar{y}$ is mean of observed data, n is the number of observations. Then, variability of the data set is measured through different sums of squares:

- $SS_{\text{tot}} = \sum_i (y_i - \bar{y})^2$, the total sum of squares (total area of red squares in Fig. 4.7)
- $SS_{\text{res}} = \sum_i (y_i - f_i)^2$, the sum of squares of residuals, also called the residual sum of squares (total area of blue squares in Fig. 4.7)

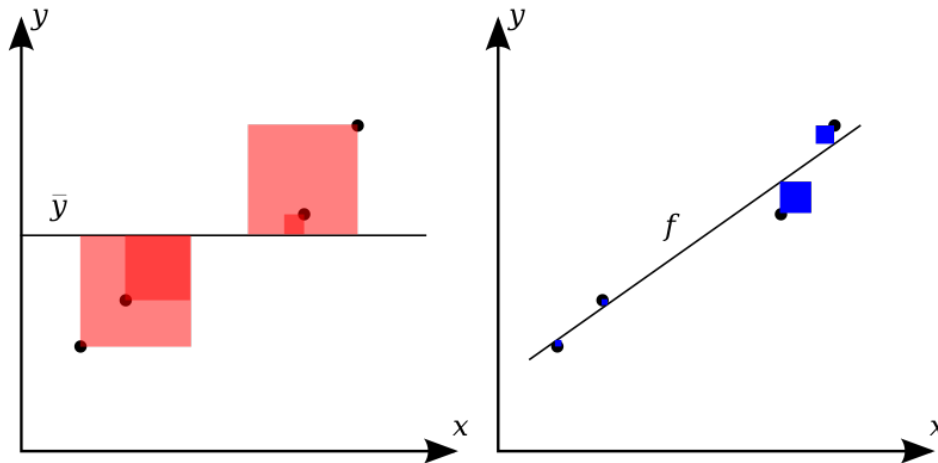


Fig. 4.7 The better the linear regression (black line on the right) fits the data in comparison to the simple average (black line on the left graph), the closer the value of R^2 is to one. The areas of the blue squares (SS_{res}) represent the squared residuals with respect to the linear regression. The areas of the red squares represent the squared residuals with respect to the average value (SS_{tot}) from Wikipedia

http://en.wikipedia.org/wiki/Coefficient_of_determination

Finally, the coefficient of determination is given as:

$$R^2 = 1 - \frac{SS_{\text{res}}}{SS_{\text{tot}}} \quad (4.3.2)$$

For multiple regression, the *adjusted* R^2 value $\bar{R}^2$ is often used instead of R^2 :

$$\bar{R}^2 = 1 - (1 - R^2) \frac{n - 1}{n - p - 1} \quad (4.3.3)$$

where n is the sample size and p is the number of independent variables.

4.4 Results and discussion

4.4.1 Coefficient of determination

After building the linear regression mode for each temperature profile, the R^2 were mapped (left in Fig. 4.8). It is obvious that most of the points are around the value of 1. The box-and-

whisker plot of R^2 exhibits that the min value is 0.011, 1st quartile is 0.960, median is 0.985, mean is 0.949, 3rd quartile is 0.995, and max is 0.999 (right in Fig. 4.8). The result shows that most of temperature profiles follow the linear distribution and they should be conductive type.

4.4.2 Identification of two types of geothermal profile

Based on Fig. 4.8, the threshold of coefficient of determination to discriminate the thermal type was chosen as 0.9. If the R^2 is larger than 0.9, it is considered to be a conduction type, otherwise it is a convection type. Fig. 4.9 shows the result of detected convection-type temperature profiles in Hokkaido area. There are 45 convection-type profiles which are mostly located near the volcanoes. This type has higher thermal gradient than the conductive type. Identification of the conductive and convective types contributes to be more accurate 3D temperature modeling by kriging than the absence of consideration.

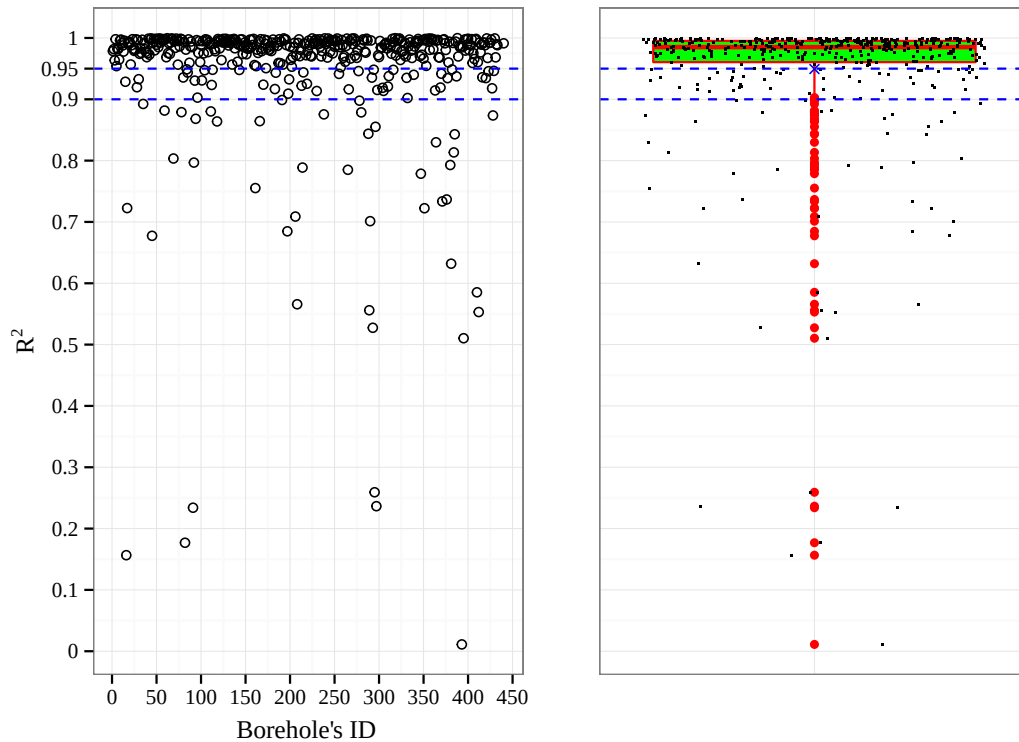
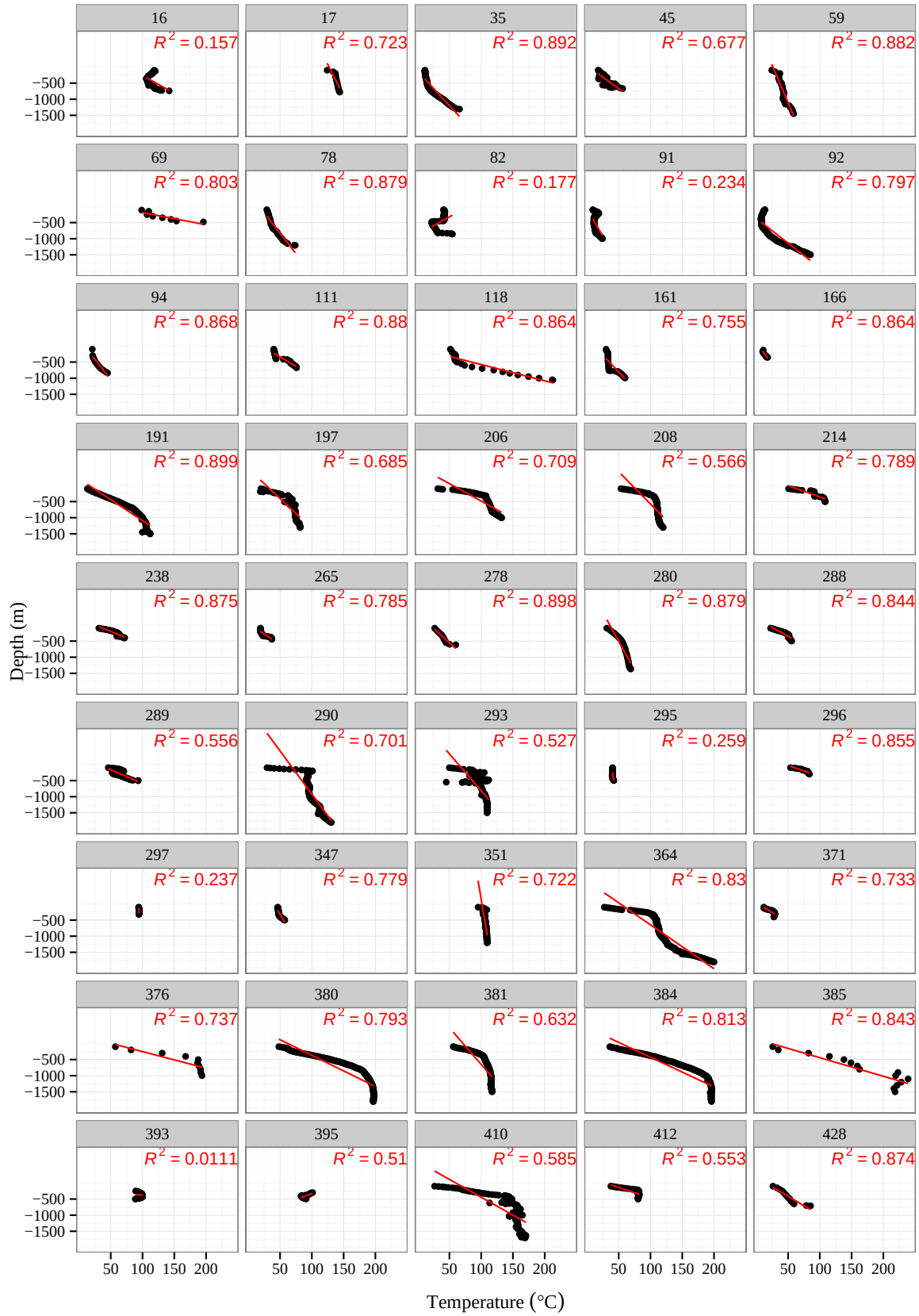


Fig. 4.8 Coefficient of determination distribution map (left) and box-and-whisker plot (right) of all temperature profiles in Hokkaido

Fig. 4.9 Temperature-logging profiles with $R^2 < 0.9$

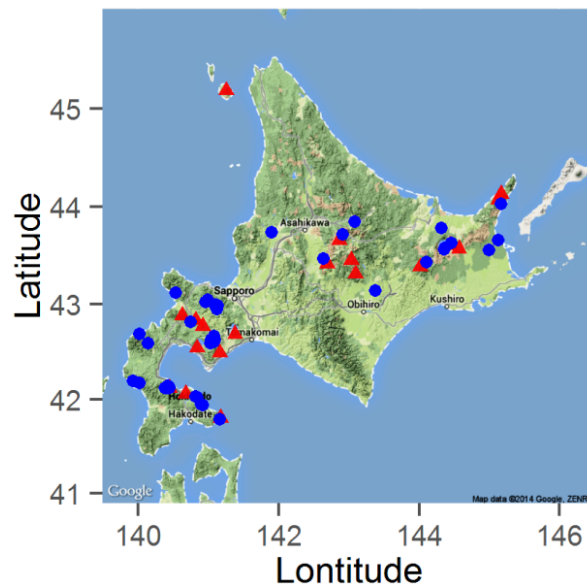


Fig. 4.10 Temperature-logging map with $R^2 < 0.9$ (blue points).

4.5 Summary

Identification of thermal type of borehole, which is related to geothermal fluid, is essential to geothermal exploration and reservoir mapping because thermal conductivity in water is relatively lower than in average rock materials. This chapter focused on identifying the two types of heat transfer in the crust, conductive and convective, from a set of temperature-logging dataset using coefficient of determination method. Threshold of 0.9 was finally chosen to discriminate the two thermal types. It was proved by the calculation that coefficient of determination was a proper index to identify conductive and convective types and be available to 3D temperature modeling.

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Chapter 5

Combination of Well-logging

Temperature and Thermal Remote

Sensing for Characterizing Geothermal

Resource

“Scientists still do not appear to understand sufficiently that all earth sciences must contribute evidence toward unveiling the state of our planet in earlier times, and that the truth of the matter can only be reached by combing all this evidence. It is only by combing the information furnished by all the earth sciences that we can hope to determine 'truth' here, that is to say, to find the picture that sets out all the known facts in the best arrangement and that therefore has the highest degree of probability. Further, we have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw.”

Alfred L. Wegener, *The Origins of Continents and Oceans* (1964)

In this chapter, A case study in Hokkaido is conducted utilizing comparison and combination of [3D](#) modeling of well-logging temperature data with Land surface temperature data derived from [TIR](#).

5.1 Introduction

After the serious nuclear power plant accident caused by the 11th March 2011 Great East Japan Earthquake and Tsunami, all nuclear power plant operations in Japan were suspended. Thus, identification of renewable energy resources for electrical power generation has become increasingly important in Japan. Geothermal, solar, wind and biomass are typical renewable energy resources. Geothermal resources are characterized by small CO₂ emissions during power generation, vast reserves in the shallow crust (< 3 km), and much higher capacity utilization ratios (over 70%) than other energy resources (I. B. Fridleifsson, 2001). In addition to the use of high temperature geothermal resources for power generation, low temperature geothermal activity has been exploited for space heating, agriculture and industrial heating processes (Barbier, 2002). Japan is part of the Pacific Ring of Fire, and contains more than 450 Quaternary volcanoes, 110 of which are currently active. As a result, Japan has abundant geothermal resources, and the eighth highest geothermal electrical power capacity in the world (Bertani, 2012).

Accurate assessment of geothermal systems including geological structures, fluid flow, and temperature distribution from the ground surface to great depths (3–10 km) is essential to enhance the use and development of geothermal resources. However, such assessments are difficult owing to the deep-seated and heterogeneous distributions of geothermal resources. Data obtained from drilling investigations (i.e. cores, geological columns, and well logs describing physical and chemical rock properties) are the most reliable and accurate sources for characterization of geothermal systems (Asaue et al., 2006; Teng et al., 2007). Drilling is the most expensive type of exploration and the amount and depth coverage of available drilling data tend to be limited. Moreover, drilling sites are generally irregularly distributed throughout the study area. TIR is an effective technique to overcome these limitations in data distributions because active geothermal fields accompany surface manifestations of the

transport of heat and mass through the crust such as volcanoes, hot springs, mud pots and fumaroles, which can be distinguished as thermal high anomalies in the LST. TIR has great potential for cost-effective geothermal resource exploration. Therefore, a combination of 3D modeling of SST using datasets composed of well-logging temperatures and LST (from TIR) is essential for a comprehensive understanding of geothermal systems and resource exploration.

The aim of the study was to develop and assess two methods suitable for 3D temperature modeling and regional LST mapping, and to identify potential areas of geothermal resources using a combination of the developed methods. Hokkaido, Japan was selected for a case study owing to the relatively abundant temperature data for the island region (Fig. 4.3). Kriging, a spatial interpolator and simulator, may be the most promising method for the 3D modeling of SST using a well-logging dataset with the above limitations (Agemar et al., 2012). Among several types of kriging, KED was selected for this study because it can incorporate essential trends such as monotonous increases of temperature with depth.

TIR has been successfully applied to detection and quantification of LST anomalies and heat discharges in geothermal fields since the 1960s (Hodder, 1970; Meer et al., 2014; Qin et al., 2011; Urai, 2002, 2000). Recently, TIR was applied to detection of hot springs using thermal infrared data from ASTER and AVIRIS (Hellman et al., 2004). Landsat band 6 imagery from TM onboard Landsat 4, 5, and ETM+ sensor onboard Landsat 7 has also been widely applied for LST studies (Andres et al., 1995; Flynn et al., 2001; Harris et al., 1999; Vlassova et al., 2014; Wang et al., 2013). Sobrino (Sobrino et al., 2004) compared three methods of retrieving LST from band 6 imagery. The latest Landsat 8 launched in February 2013 ensures the continuous use of Landsat series imagery for LST retrieval (Jiménez-muñoz et al., 2014; Yu et al., 2014). In this study, the Landsat 8 TIRS band 10 imagery was used for the LST analysis. Understanding the surface energy balance and underground heat transfer will contribute to identification of geothermal resource areas in the study area as well as in other regions worldwide.

5.2 Study Area and Data

5.2.1 Geological structure

Hokkaido in its current form was structured after the middle Miocene by the collision of Kuril Arc and the Northeast Japan Arc at the middle of Hokkaido (Kimura, 1996). As a result, Hokkaido consists of three main parts, an eastern region (part of the Kuril Arc), central region (the arc-arc collision zone), and a western region (part of the Northeast Japan Arc) (Fig. 5.1). The volcanic front runs nearly east-west from the eastern region through the central region, then turns to the south in the western region (Fig. 5.1). This front is parallel to the Kuril Trench and the Japan Trench. The mountains in Hokkaido generally have gentle slopes in the northern part and steep slopes in the southern part. Similar to other areas in Japan, Hokkaido is seismically active, with six most active volcanoes, Mt. Shiretoko io-zan, Mt. Meakan-dake, and Mt. Tokachi-dake located in the eastern part of the Hokkaido island, and Mt. Tarumae-san and Fuppushi-dake, Mt. Usu-zan and Mt. Hokkaido-Komagatake (Fig. 4.3 and Fig. 5.5) (Siebert et al., 2010).

The main portion of Hokkaido contains 80 Quaternary volcanoes that were active during the Quaternary Period (ca. 2.6 Ma to present), including 20 that have erupted within the past 10,000 years or are under vigorous fumarolic activity. The distribution of Quaternary volcanoes and active volcanoes (Fig. 4.3) were obtained from the websites of Geological Survey of Japan (GSJ), The National Institute of Advanced Industrial Science and Technology (AIST) (AIST, 2013).

5.2.2 Dataset of well-logging temperature

The present dataset of temperature logging originates from the temperatures profiles in Japan database compiled by the JAEA in 2004 (JAEA, 2004). The borehole temperature logging data used in this study is a subset of the above datasets. After checking all temperature data

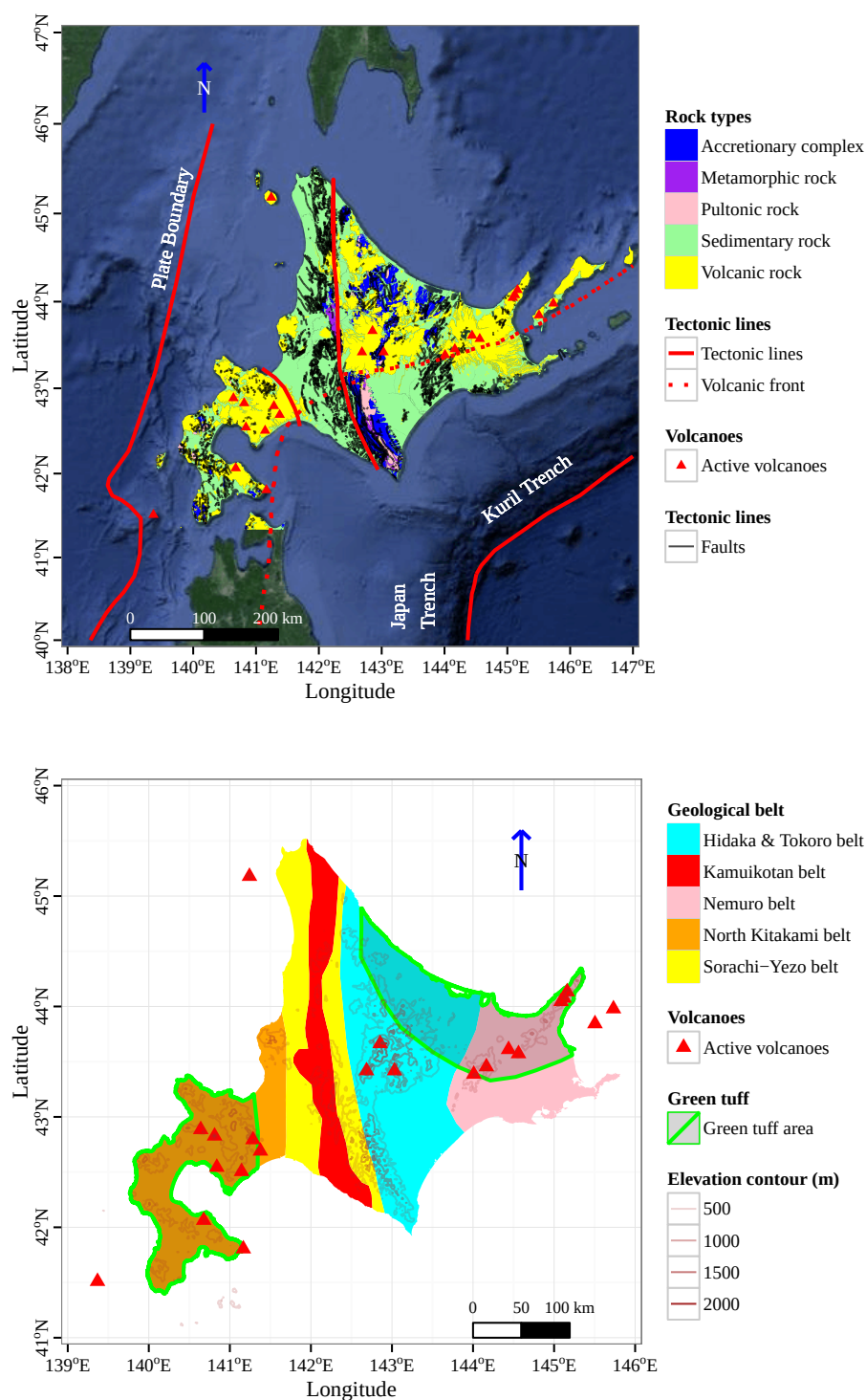


Fig. 5.1 Geological settings and main rock types of Hokkaido island (Geological Survey of Japan, n.d.) (top), and distributions of geological belts, green tuff areas and elevation contours (Geological Survey of Japan, n.d.; Minato et al., 1956) (bottom).

and removing 67 outliers that showed extremely low temperatures at deep depths (Tian and Koike, 2014), 28,476 datapoints from 433 drilling sites within an area of 83,453.57 km² were selected. The lengths (i.e., depths from the ground surface to the bottom of boreholes) ranged from 241 m to 2200 m, with 70 boreholes less than 500 m in length, 129 between 500 and 1000 m, 182 between 1000 and 1500 m, 51 between 1500 and 2000 m, and 1 longer than 2000 m (Fig. 4.3, 5.2 and 5.3). The first quartile, mean, median, and third quartile of the total length are 615 m, 980 m, 1001 m, 1270 m, respectively (Fig. 5.2).

As shown in all temperature profiles (Fig. 5.3), the temperatures increased with increasing depth, but the gradients varied greatly with borehole location. 3 increasing trends were observed forming a linear, logarithmic, and exponential curve. Linear increases signify that thermal conduction governs the temperature change, while convection occurs at discharge areas showing logarithmic increases. The exponential curve reflects low temperatures in shallow depths owing to descending fluid flow in a recharge area. The average temperature gradient is 81 °C/km (Fig. 5.3), which is about three times larger than the average gradient of shallow crust (25-30 °C/km) (I. Fridleifsson et al., 2008). In addition, the mean and median temperatures increase with increasing depth intervals, and the range of temperature varies with drill depth (Fig. 5.4). The increase in the range indicates that temperature differences among sites become greater with depth.

5.2.3 TIR data

Two sensors, OLI and TIRS, are onboard the Landsat 8 satellite, which was launched and operated by NASA and the USGS (NASA, 2014). There are nine spectral bands in OLI for measuring surface reflection (NASA, 2014): coastal/aerosol (0.435 - 0.451 μm), visible blue (0.450 - 0.515 μm), green (0.525 - 0.600 μm), red (0.630 - 0.680 μm), Near InfraRed (NIR) (0.845 - 0.885 μm), Short Wave InfraRed 1 (SWIR1) (1.560 - 1.660 μm), Short Wave InfraRed 2 (SWIR2) (2.11 - 2.29 μm), cirrus (1.360 - 1.390 μm), and panchromatic mode (0.500 - 0.680

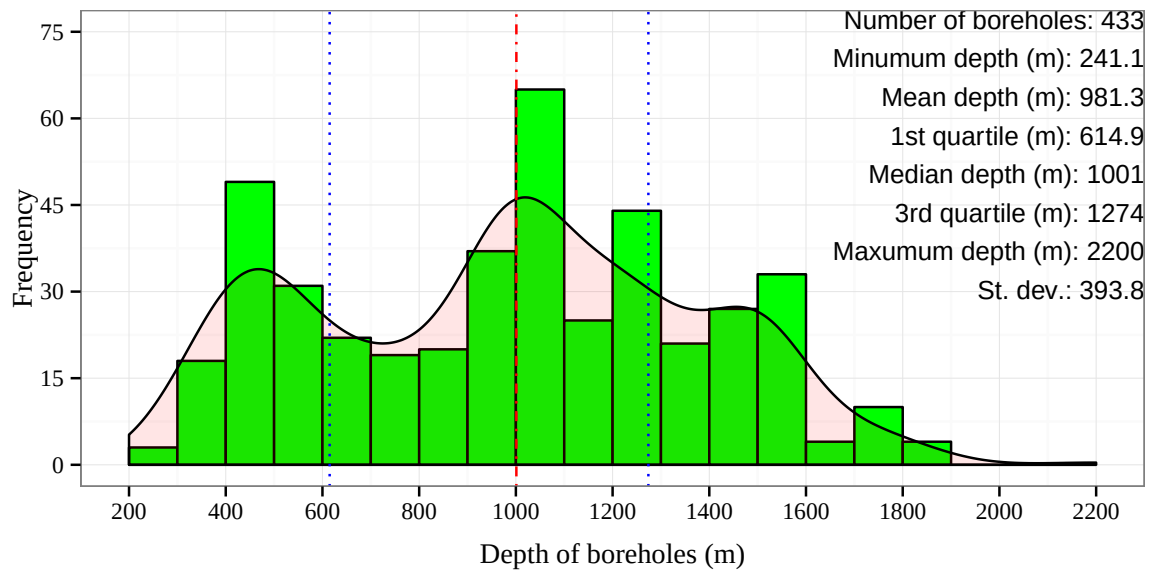


Fig. 5.2 Histogram of borehole depths. The dashed red and blue lines and curve denote median, 1st and 3rd quartile depth and density, respectively.

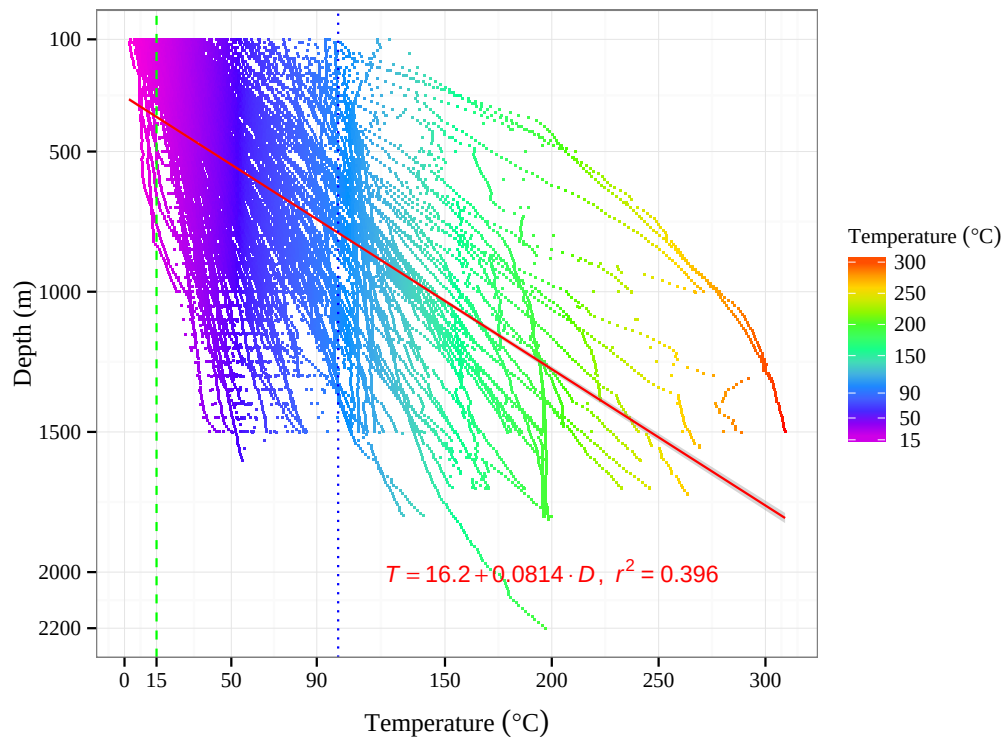


Fig. 5.3 All temperature profiles with depth. The red line denotes a linear regression of the relationship between temperature and depth and shows a geothermal gradient 81 °C/km. The dotted blue line shows 100 °C.

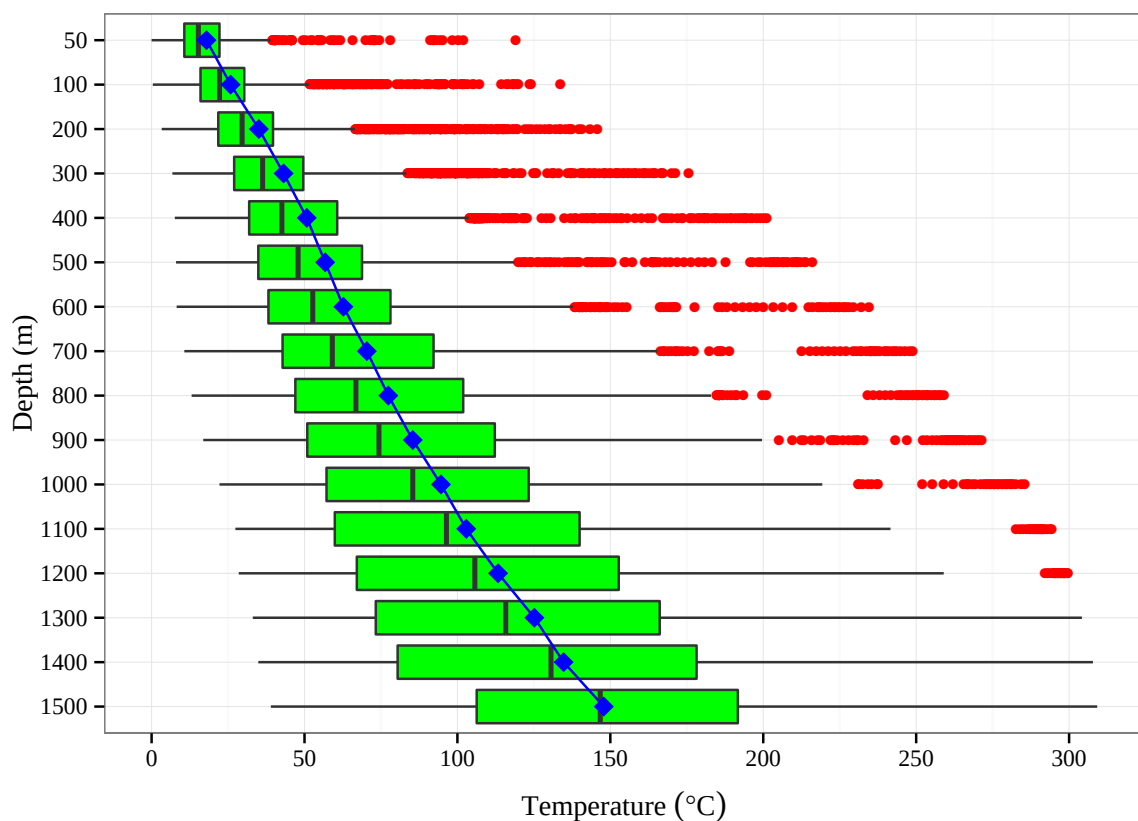


Fig. 5.4 Box-and-whisker plot of temperature data from each depth at 100 m intervals. The blue diamonds and red circles denote mean values of the same depth group and outliers, respectively.

Table 5.1 Details describing thirteen selected Landsat 8 scenes

Landsat 8 Identifier	Acquisition	Cloud cover(%)	Sun elevation($^{\circ}$)	Sun azimuth($^{\circ}$)
LC81050292014153LGN00	2014-06-02	0.37	63.11	139.90
LC81050302014153LGN00	2014-06-02	0.34	63.98	137.30
LC81060292014176LGN00	2014-06-25	1.27	63.64	136.50
LC81060302013189LGN00	2013-07-08	5.85	63.65	134.81
LC81060312013189LGN00	2013-07-08	0.38	64.42	132.03
LC81070282013292LGN00	2013-10-19	0.26	32.76	163.35
LC81070292013292LGN00	2013-10-19	2.66	34.03	162.60
LC81070302013292LGN00	2013-10-19	2.11	35.30	161.83
LC81070312014119LGN00	2014-04-29	0.56	58.22	143.23
LC81080282013283LGN00	2013-10-10	0.40	35.91	161.91
LC81080292014078LGN00	2014-03-19	10.06	41.32	151.96
LC81080302014110LGN00	2014-04-20	3.85	54.40	146.81
LC81080312014110LGN00	2014-04-20	1.45	55.43	145.09

μm). In addition, there are two bands in **TIRS** for measuring radiation ($10.60 - 11.19 \mu\text{m}$ and $11.50 - 12.51 \mu\text{m}$). Thirteen scenes from band 10 ($10.60 - 11.19 \mu\text{m}$) obtained under cloud cover of less than 10% during spring, summer, and fall were selected as suitable **TIR** imagery to clarify the **LST** distribution on Hokkaido (Table 5.1 and Fig. 4.3). The images are the best quality for each scene, with the path and row numbers in Fig. 4.3.

In addition, a **LULC** map of Hokkaido with a resolution of 30 m generated by **Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Center (EORC)** (JAXA, 2014) was used to estimate emissivity and anthropogenic impacts on thermal anomalies. This **LULC** map was produced using **The Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2)** image data with a resolution of 10 m onboard **ALOS**. The categories of **LULC** are water, urban, paddy field, crop field, grass land, deciduous forest, evergreen forest, bare land, and snow and ice (Fig. 5.5).

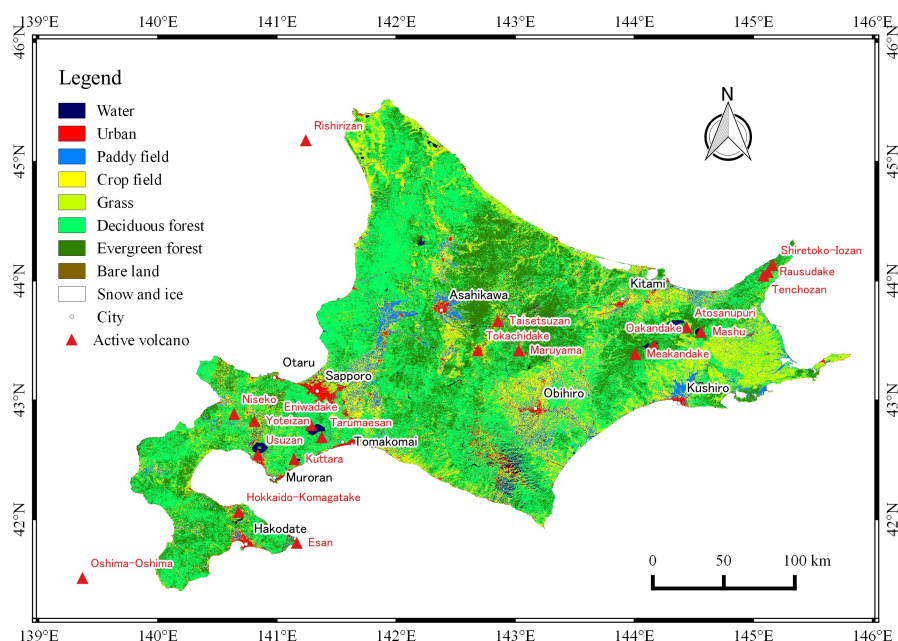


Fig. 5.5 Land-Use and Land-Cover (LULC) map over the study area generated using the **Advanced Land Observing Satellite (ALOS) The Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2)** image dataset by **Japan Aerospace Exploration Agency (JAXA)** (JAXA, 2014).

5.3 Methods for estimating SST and LST

5.3.1 Geostatistical estimation of 3D subsurface temperature

As shown in Fig. 5.3, the temperature data are not statistically stationary because they increase with depth. **Kriging with External Drift or trend (KED)** (Eq. 2.2.6) is suitable to produce a spatial model for regionalized data with significant spatial trends, such as the temperature logging data used in this study. **KED** incorporates a local trend within the neighborhood search window as a smoothly varying function, which is usually a polynomial function of the coordinates, and then estimates the trend component within the window and a value at the unsampled point by simple kriging using the residual sample data. This residual is equal to the sample value minus the local mean in the window (Bourennane et al., 2000). **KED** is calculated by 2.2.6.

A workflow of **KED** is shown in Fig. 5.6. For simplification, a global linear trend related to the physics of conduction was adopted for the log-transformed temperature data used for **3D KED** estimation. This estimation also assumed the steady state of temperature. The log-transformation was conducted to reduce data distribution bias and approximate a normal distribution, a suitable condition for geostatistical application. Prior to analysis, it was necessary to generate a variogram. Fig. 5.7 shows the resultant omnidirectional experimental variogram and its approximation by the best-fitted variogram model. A nested structure clearly appeared in the variogram, indicating a mixture of short and long spatial correlation structures. The short structures primarily expressed the correlation along the vertical direction and were approximated by a Gaussian model with a range (maximum correlation distance) of 700 m and sill of 0.155. In contrast, the long structure reflected the lateral direction and was approximated by the spherical model, with a much longer range of 35 km and a sill of 0.125.

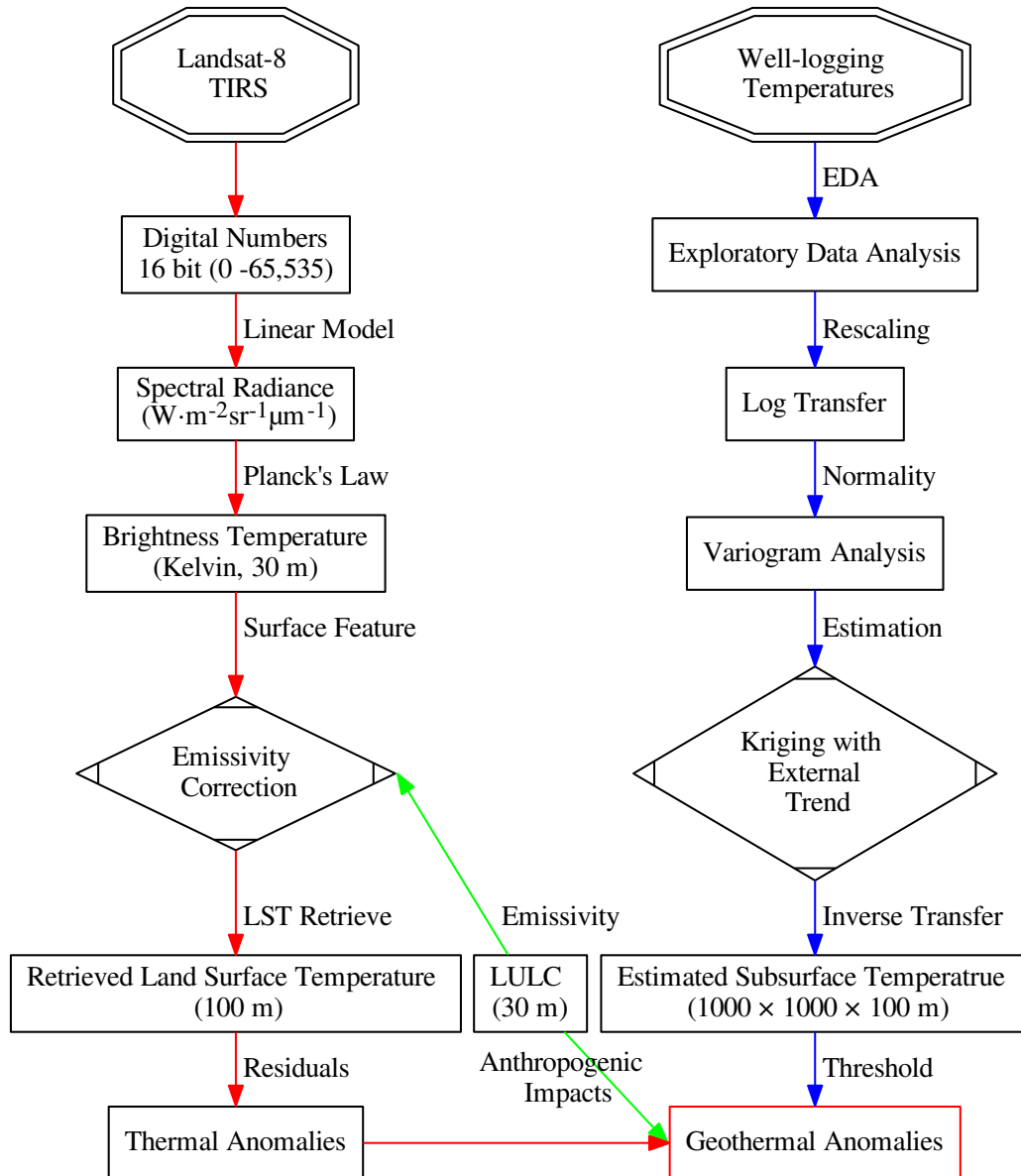


Fig. 5.6 Workflows of subsurface and surface temperature modeling to detect high temperature anomaly zones based on a combination of the well-logging temperatures database and satellite Thermal InfraRed Sensor (TIRS) images.

5.3.2 LST algorithm

Many algorithms based on different assumptions have been proposed for estimation of LST from satellite TIR image data to date (Li, 2012; Li et al., 2013). For this investigation, an algorithm proposed by Artis et al. (Artis et al., 1982) was selected because it requires only one parameter (emissivity of surface material), which was suitable here because LST residuals from many low cloud cover scenes with different seasons were used. The method used to obtain the LST map from the Landsat 8 TIRS band 10 image data using a set of R (R Core Team et al., 2014) scripts is summarized in Fig. 5.6. First, DN was converted to $B(\lambda, T)$, which is the at-sensor spectral radiance at the middle wavelength of band 10 ($\lambda = 10.9\mu\text{m}$). T_B at sensor or TOA was then calculated using Eq. 2.1.2. Next, T_B was corrected by considering the LSE, ϵ . The values of ϵ were assigned to each pixel based on the categories shown in the LULC map (Fig. 5.5). Finally, LST was calculated from T_B and ϵ (Table 5.2) using equation (Artis et al., 1982):

$$LST = \frac{T_B}{1 + (\lambda \times T_B / c_2) \times \ln \epsilon} \quad (5.3.1)$$

Because of the mixture of seasons, the LST maps derived from the image data in Table 5.1 cannot be directly compared with each other. To reduce this seasonable change effect in LST, each LST map was normalized by subtracting the mean LST value, LST_m as:

$$LST_n = LST - LST_m \quad (5.3.2)$$

where LST_n is normalized LST, LST_m is mean LST of each Landsat imagery. All LST_n maps were connected to highlight high temperature anomaly zones.

Additionally, a suite of open source R packages (raster (Hijmans, 2014), sp (Pebesma and Bivand, 2014), rgeos (Bivand and Rundel, 2014), rgdal (Bivand, Keitt, et al., 2014), gdalUtils (Greenberg et al., 2014), landsat (Goslee, 2012), wrspathrow (Zvoleff, 2014), gstat (Pebesma

Table 5.2 Emissivity assigned by land use and land cover data (Fig. 5.5)

LULC code (JAXA, 2014)	LULC category	Emissivity(ϵ)	Color in Fig. 5.5
1	Water	0.99	darkblue
2	Urban area	0.93	red
3	Paddy field	0.96	skyblue
4	Crop field	0.95	yellow
5	Grass land	0.96	yellowgreen
6	Deciduous forest	0.97	springgreen
8	Evergreen forest	0.98	forestgreen
10	Bare land	0.92	saddlebrown
11	Snow and ice	0.91	white

and Graeler, 2014), maptools (Bivand and Lewin-Koh, 2014), ggplot2 (Wickham et al., 2014), ggmap (Kahle et al., 2013), and rasterVis (Perpinan Lamigueiro et al., 2014) were used for data downloads, analyses and mapping in this study. We developed an R software package for TIR image analysis and LST mapping in the R programming language. The source codes of the package are freely available to download from <https://github.com/bwtian/TIR> (Tian, 2014).

5.4 Results

5.4.1 Characterization of 3D subsurface temperature modeling

The 3D SST (Fig. 5.8) was calculated for depths of 100 m to 1500 m over Hokkaido by KED using the model (Fig. 5.7) and a unit grid size of 1000 m $\times$ 1000 m $\times$ 100 m. The result is shown by slices of 3D SST distributions at the same depth (Fig. 5.8). To confirm the estimation accuracy of the 3D SST, cross-validation was conducted for the sampled temperature value and the predicted value by KED and the results were reported as a linear correlation coefficient (r). The r value was 0.97, indicating that the SST model is reliable.

Temperature distributions at different depths are shown in Fig. 5.8. The distributions were characterized by local high temperature zones over 150°C at all depths, with temperature ranging from 50 to 300°C. The local anomalies were limited to locations on the eastern border, central, and western parts of the study area at shallow depths of no more than 500 m below sea

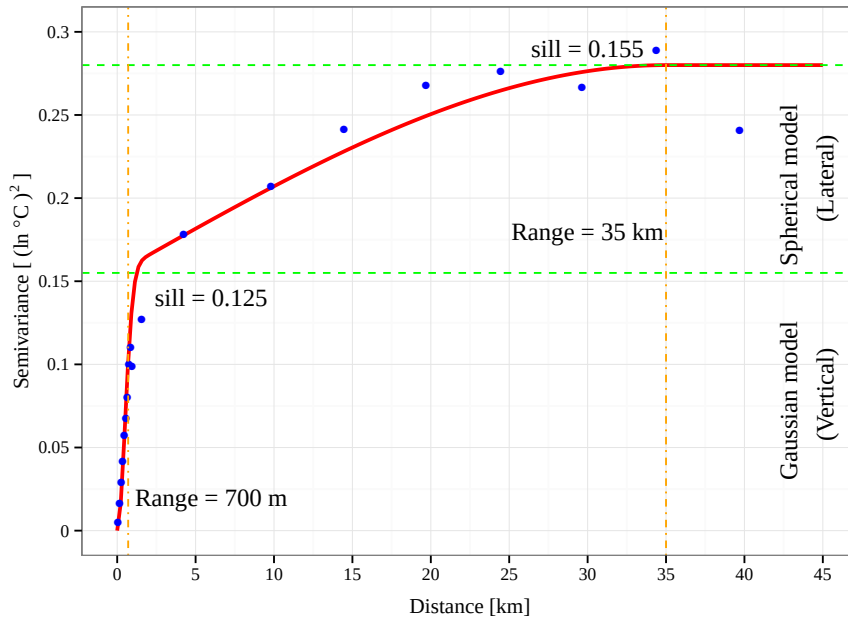


Fig. 5.7 Nested 3D variogram model (red curve) showing a mixture of two spatial correlation structures of temperatures data, short along the vertical direction and long along the lateral direction. The blue dots, green dashed lines, and orange dashed lines reflect experimental variograms, sills, and ranges, respectively.

level (b.s.l.), which is concordant with the locations of active volcanoes. The high anomaly zones are more evident and extend with increasing the depth. One remarkable feature is that the high temperature zones extend into the western region (Northeast Japan Arc, Fig. 5.1), while temperatures in the central region (arc-arc collision zone, Fig. 5.1) are generally low, and those in the middle of the eastern region (Kuril Arc part, Fig. 5.1) are high relative to the surrounding areas. This feature becomes greater at depths of 1500 m b.s.l. or more. In general, temperatures in the western region are higher than in the other two regions, which agrees with the large distribution frequency of Quaternary volcanoes. As shown in Fig. 5.8, high SST zones mostly overlapped with the distribution of Quaternary volcanic rocks areas (Fig. 5.1).

5.4.2 LST

MODIS LST has been widely used to verify LST accuracy through Landsat series or remotely obtained images (Qin et al., 2011; Srivastava et al., 2009). The differences between MODIS

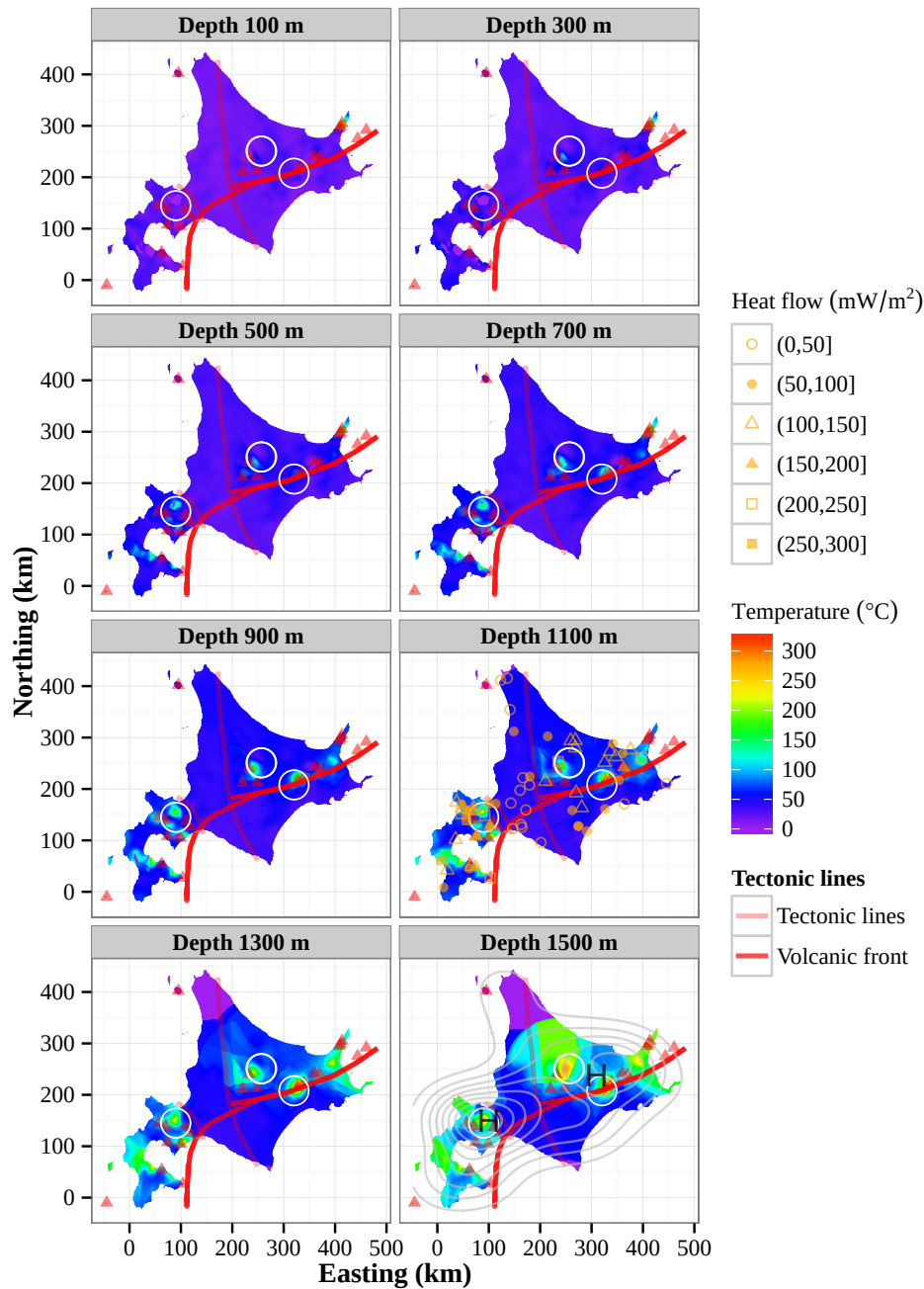


Fig. 5.8 Temperature distribution at the same depth based on temperature logging data and [Kriging with External Drift or trend \(KED\)](#) from 100 to 1500 m b.s.l. at 200 m intervals, superimposed on the heat flow data modified from Tanaka et al. (2004) (Tanaka, 2004; Tanaka et al., 2004) (at 1100 m), and their contour map by weighted kernel density (at 1500 m). Purple at depths deeper than 1100 m b.s.l indicates that the area is outside the calculation region due to insufficient temperature data for KED. Red triangles and white circles indicate active volcanoes and local high temperature zones, respectively.

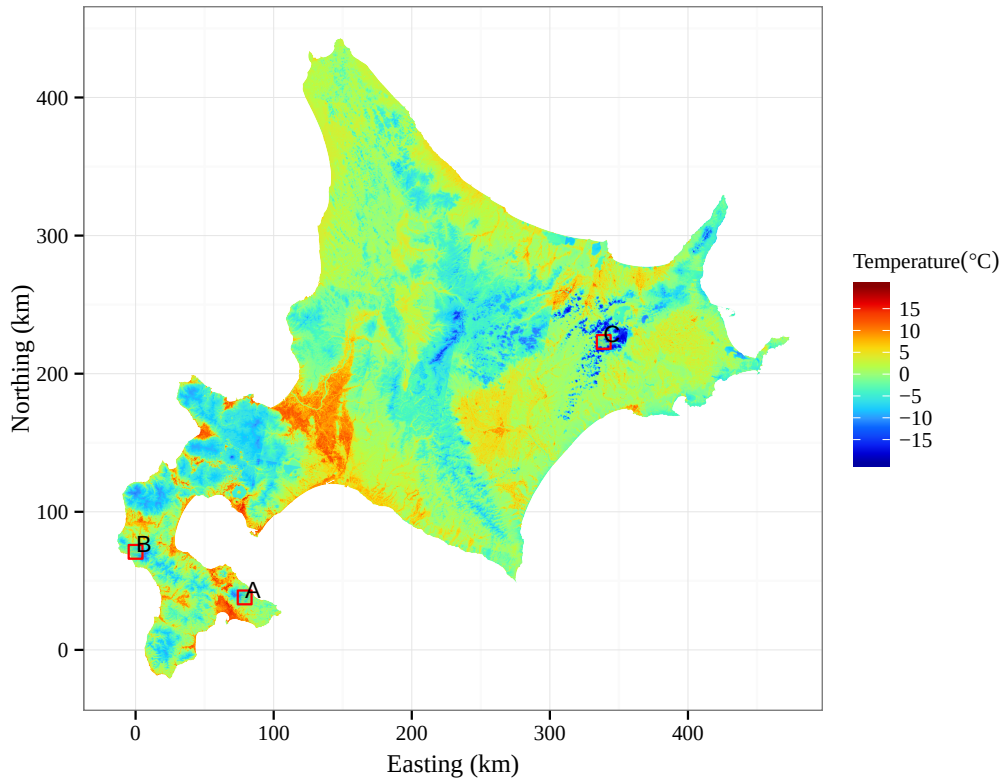


Fig. 5.9 Land Surface Temperature (LST) map produced from 13 Landsat 8 Thermal InfraRed Sensor (TIRS) images and connection of each scene subtracted from the mean temperature.

LST values and ETM+ are reportedly smaller than 2 °C (Srivastava et al., 2009). In addition to the KED results, LST maps derived by Eq. 5.3.1 were verified by comparison with the MODIS LST maps on the same acquisition dates as the 13 scenes. This was the only method of verification used in the present study because there were insufficient in-site surface temperature data available. As in (Srivastava et al., 2009), the average differences in the LST values at corresponding locations were smaller than 2 °C for all scenes, which indicates that the LST results were accurate. Accordingly, the LST maps can be effectively used to characterize LST over the study area. Connected LST_n highlights high temperature zones (Fig. 5.9), which were primarily located in anthropocentric areas such as urban areas, paddy fields and crop fields. Among these regions, urban areas had the highest LST. The low LST extends into high elevation areas covered by forest. By excluding all high LST associated with anthropocentric

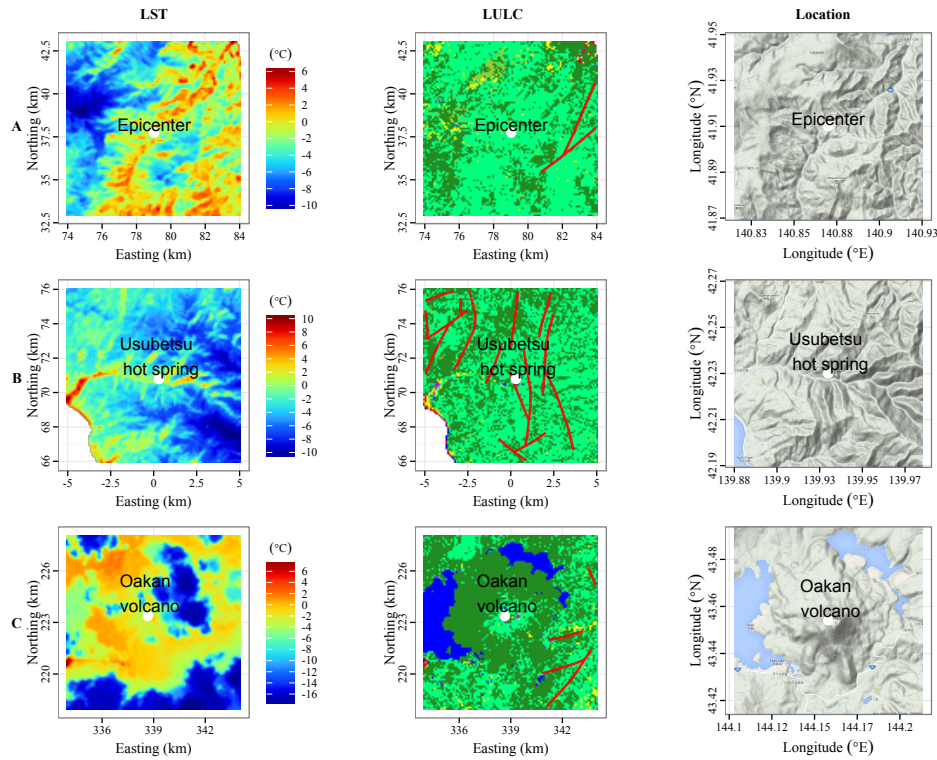


Fig. 5.10 Comparison of **Land Surface Temperature (LST)** (derived from the scene average) and **Land-Use and Land-Cover (LULC)** in the three zones shown in Fig. 5.9 which are situated at local high temperatures, specially $> 150^{\circ}\text{C}$ at 1500 m b.s.l. (Fig. 5.8). The location maps are modified from Google terrain map. The red lines indicate faults. See Fig. 5.5 for the color legend of **LULC**.

effects, three zones (A, B, and C in Fig. 5.9) were identified for examination of the correlation between **LST** and **SST** values, as well as for assessment of their geothermal potential. These three zones were selected because they were all are situated at local high temperatures, with 150°C at 1500 m b.s.l. **LST** maps in the three zones covering $10\text{ km} \times 10\text{ km}$ are compared with the **LULC** maps and the location maps (from Google terrain map) in Fig. 5.10. At all zones, **LULC** fell into the category of deciduous or evergreen forest (Fig. 5.10); therefore, the **LULC** effects on **LST** must be small. Nevertheless, all zones contained high **LST** anomalies, being 3 to 9°C higher than the surrounding areas. Based on these results, the residual **LST** can contribute to detection of high temperature zones connected with the high **SST** in shallow and deep depths and favorable geothermal resources.

5.5 Discussion

5.5.1 Geological interpretation of the crustal temperature distribution

The SST results can be characterized based on the differences among the three regions on Hokkaido, with the highest values being observed in the western region and the lowest in the central region. The SST model is harmonious with the terrestrial heat flow map retrieved from the database of geothermal gradients and heat flow data in and around Japan (Tanaka, 2004; Tanaka et al., 2004), with the highest temperature zones at 1500 m b.s.l. being found in the western region (Fig. 5.9), which is consistent with the extremely high heat flow region (Fig. 5.8). Moreover, the presence of relatively high temperatures at shallow depths (e.g., 200 °C at 500 m b.s.l.) in the western region and a portion of the eastern region indicates that the heat sources in these regions may be shallower than in the surrounding areas. Based on the geophysical features, the temperatures in these western region were inferred to increase to 1000 °C at depths of 15-20 km depths, whereas they only increased to 200 °C at the same depth range in the central region (Ehara, 1972).

From a geological viewpoint, the western region with high SST is overlain by green tuff (Fig. 5.1) which is a product of submarine volcanic activity that mainly occurred in the Miocene (Minato et al., 1956). The cause of the high temperatures in the eastern region can also be attributed to igneous activity originating from subduction of the Pacific Ocean plate because Hokkaido is situated in a subduction zone at the northwestern margin of the Pacific Ocean. Magma is generated under island arcs in response to subduction of the Pacific Ocean plate and partial melting of the crust. The formation and location of the volcanic front (Fig. 5.1) likely originated from this magma.

Formation of the volcanic front is related to the distribution of trenches (Fig. 5.1). Based on the above generation mechanism of high temperature zones, another high temperature zone have high possibility to appear on the southeastern side along the volcanic front in the central

region. However, the area was found to be dominated by low temperatures that continue to 1500 m b.s.l. (Fig. 5.8). Two narrow metamorphic zones, the Sorachi-Yezo belt and the Kamuikotan belt, are distributed around the central region (Fig. 5.1), which might have interrupted the geothermal activities of the island arc by large blocks of serpentinite and high-pressure terrane (Banno et al., 1992; Ehara, 1972). A sedimentary layer with a thickness of approximately 3-9 km (Kametani et al., 1964; Minato et al., 1956) characterized by low heat production originating from radioactive decay and low thermal conductivity may be other factors responsible for the low temperatures in the central region.

5.5.2 LST anomalies and geothermal potential

LST is predominately controlled by solar radiation, to a lesser degree by the Earth's interior heat, and in some cases primarily by soil heat flux (Guo et al., 2002). Excessive soil heat flux transferred to the land surface via conduction and convection causes LST anomalies, with temperatures that are higher than the surrounding areas. Accordingly, LST anomalies signify the existence of heat sources at relatively shallow depths and the formation of thermal channels, which can be related to the high potential for use as a geothermal resource. Another possible approach is to correlate LST with deeper thermal structure by the methods of Mareschal et al (Mareschal et al., 1989) which calculated the subsurface temperature from the surface heat flow data by the downward continuation techniques. The method were well applicable in two different settings, one was assumed to be conductive equilibrium and the other one was characterized by hydrothermal convection. As mentioned above, LST anomalies can be separated into those of urban origin and those associated with the subsurface heat source. Because the present study area is extensive, regional LST is certainly affected by LULC anomalies, particularly urban heat islands that greatly enhance LST and produce local anomalies. Such anomalies should be excluded from sites assessed as potential geothermal resources.

Based on these findings, we correlated areas of high SST with LST anomalies for the above three (A to C) zones. As shown in Fig. 5.10, all of the zones considered contained faults, which can be paths of hydro-thermal ascent flow and heat transfer. These geological conditions indicate that the three zones considered have high potential for geothermal resources. Indeed, there is one hot spring, Usubetsu in zone B (Fig. 5.10). Additionally, zone C is located in the volcanic area containing a Quaternary volcano, Oakan-dake. Although no manifestations were observed in zone A, an M 4.2 earthquake occurred within this zone on April 16, 2004, suggesting that there is a fault within the zone. Taken together, these findings demonstrate the high geothermal potential in the three zones. Consequently, use of a combination of LST anomalies detected from Landsat 8 TIRS image data by SST modeling is a practical and effective method for evaluation of geothermal potentials over a wide area

5.6 Summary

A set of the 28,476 well-logging temperature datapoints collected from 433 sites and 13 Landsat 8 TIRS images were used to clarify the extensive variability of temperatures in the upper crust and on the surface over Hokkaido in northern Japan. The SST model was constructed using the dataset and a geostatistical method, KED while the LST map was first produced using the LSE based universal algorithm by Artis et al. (Artis et al., 1982), and then transformed into the residual form by subtracting the scene average temperature to detect local thermal anomalies. Remarkable features were detected from the SST model by KED; specifically, high temperature zones were mostly located in the western region and a part of the eastern region in accordance with the distribution of Quaternary volcanoes and high heat flow, while the central region was dominated by low temperatures due to the thick cover of sedimentary rocks.

Although LST is mostly controlled by LULC, such as urban areas and topography, high temperature anomaly zones were detected in the high SST areas. These findings demonstrate

the effectiveness of the combination of subsurface and surface temperatures using geostatistical spatial modeling and TIRS remote sensing for identification of zones with high potential for geothermal resources. However, the effects of heat generated by urban activity and topography should be investigated in detail in a future study. A study is currently being conducted to develop a heat flux map using the combination approach described herein.

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Chapter 6

Extensive 3D Modeling of Shallow Geothermal Resources over Japan Island

“ There is an urgent need to stop subsidizing the fossil fuel industry, dramatically reduce wasted energy, and significantly shift our power supplies from oil, coal, and natural gas to wind, solar, geothermal, and other renewable energy sources.”

Bill McKibben, *environmentalist*

“ The future is green energy, sustainability, renewable energy.”

Arnold Schwarzenegger, *actor and politician*

In this chapter, six geothermal systems in Japan are firstly defined according to different tectonic settings, volcano front, fault zones and geography. Then, 3D modeling of crustal temperature of each geothermal systems are performed to give an estimate of the geothermal potential over Japan.

6.1 Introduction

Inferring the available energy is a guide for estimating the viability of the geothermal resource (Calcagno et al., 2014; Kohl et al., 2003; Muffler et al., 1978). Assessment of deep geothermal potential is of great help for further exploration and exploitation of such energy resource in Japan. Due to various geological settings, faults, volcanic zones and topographies, the geothermal systems are widely distributed under different conditions. Therefore, it is difficult to make a variogram or geostatistical modeling in the wide area for this lack in stationarity. Based on different tectonic settings (Plate, Arc, and Tectonic Line), volcano front, fault zones and geography, I divided the Japan land into six zones of different geothermal systems: Hokkaido, Northeast of Honshu, Center of Honshu, Southwest of Honshu and Shikoku, Kyushu, Nansei Islands and Izu-Bonin geothermal systems (Fig. 6.1, Fig. 6.2 and Table 6.1). The distribution of active and Quaternary volcanoes are mapped overlapped on six divided geothermal systems (Fig. 6.2). It is clear that most of volcanoes are distributed in Hokkaido, Northeast of Japan, Izu-Bonin islands and Kyushu areas. For the spatial continuity

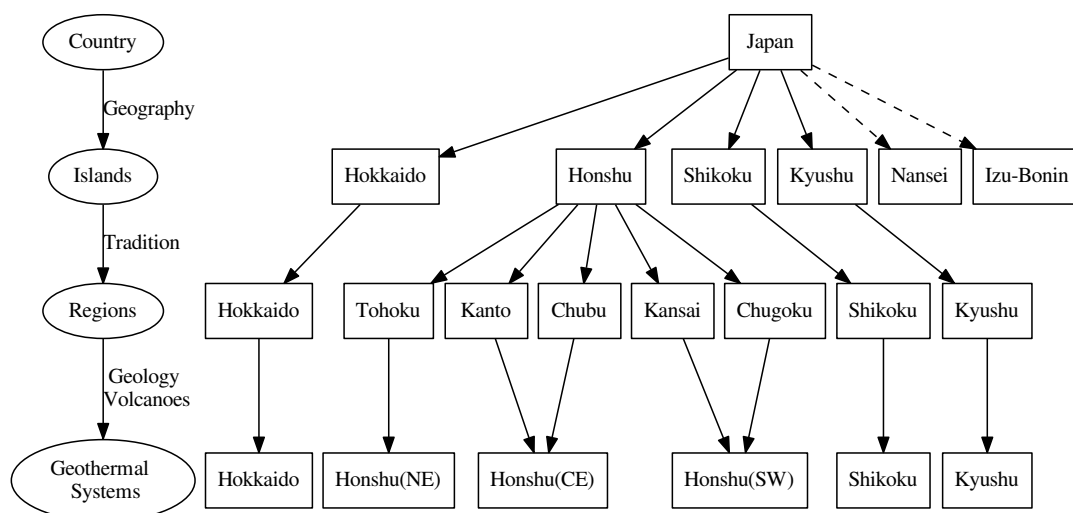


Fig. 6.1 Geothermal systems of Japan.

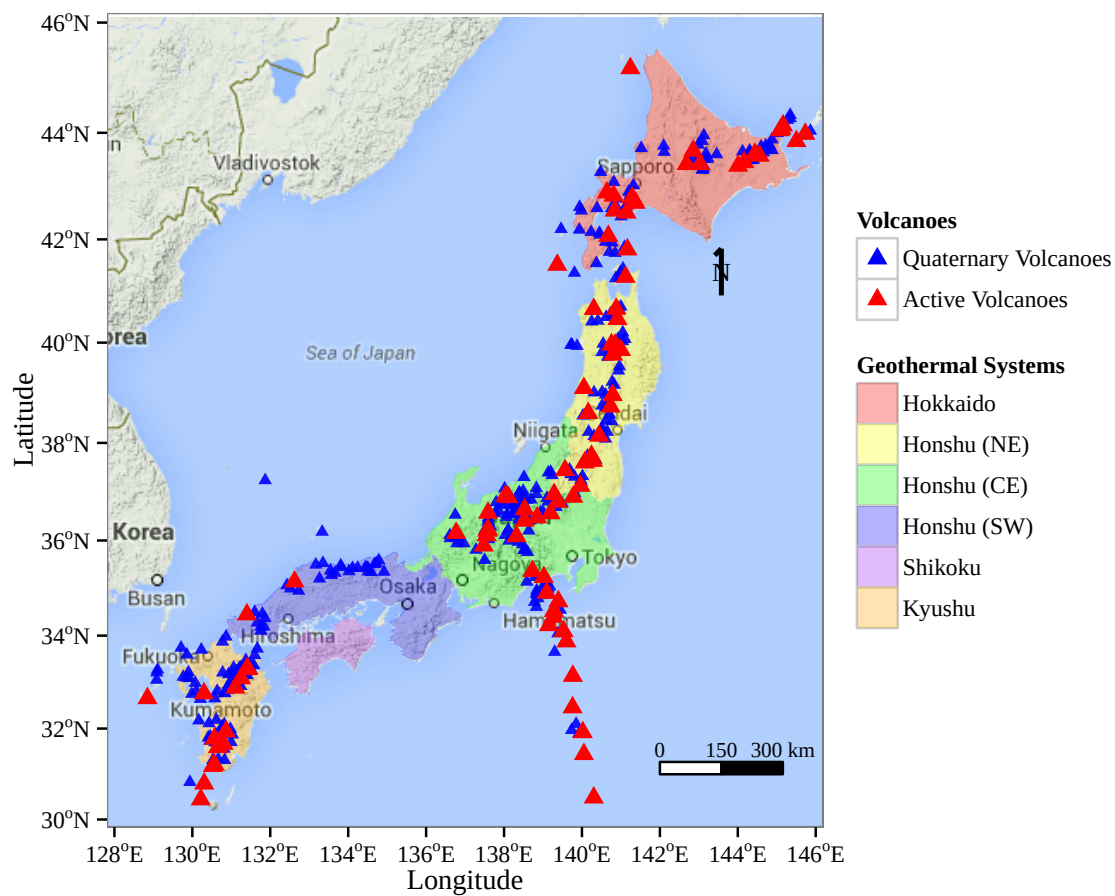


Fig. 6.2 Geothermal system zones divided in Japan showed in different colors. The red and blue triangles are denote active and Quaternary volcanoes, respectively.

of the study area in geostatistical modeling, the six divided geothermal systems in this thesis only comprise the main island of Japan. Therefore Izu-bonin Islands, Okinawa and southern islands excluded from this study due to shortage of data.

6.2 Data resources

The borehole data set was acquired from the temperature profiles in Japan dataset which was compiled JAEA in 2004 (JAEA, 2004). The active volcanoes data acquired from the website

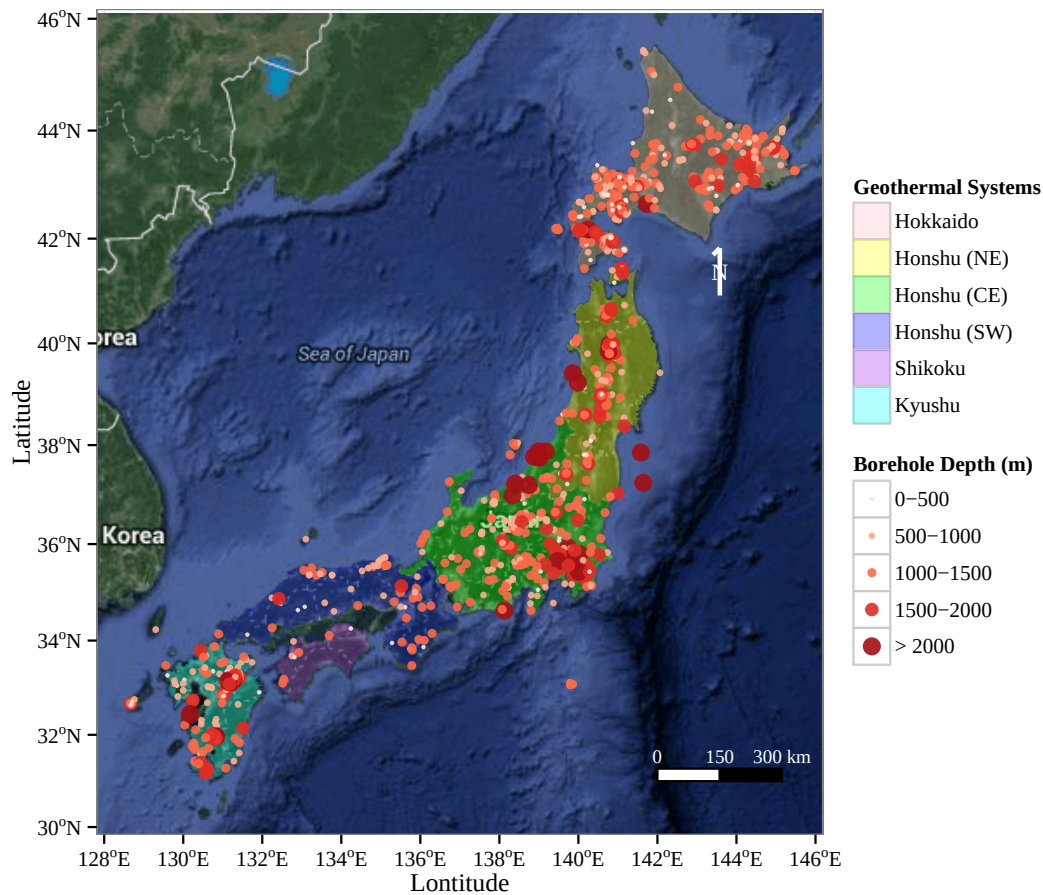


Fig. 6.3 Borehole data and its distribution in Japan.

of Japan Meteorological Agency. There are more than 110 active volcanoes, 450 Quaternary volcanoes and 27,000 hot springs located in Japan. The statistics of hot spring data is from the website of Ministry of the Environment Government of Japan.

The distribution of borehole is shown in Fig. 6.3. There are 1198 available well sites with 88,629 data samples located around whole Japan island. The minimize depth of Borehole is 240 m and maximum is 6310 m. However, most borehole depth are around 1000 m, where the mean, median, first quartile and third quartile is 1060 m, 1000 m, 660 m and 1310 m respectively. Figure 6.4 shows the distribution of boreholes and temperature samples in each divided geothermal system areas. Hokkaido have most boreholes and temperature samples which

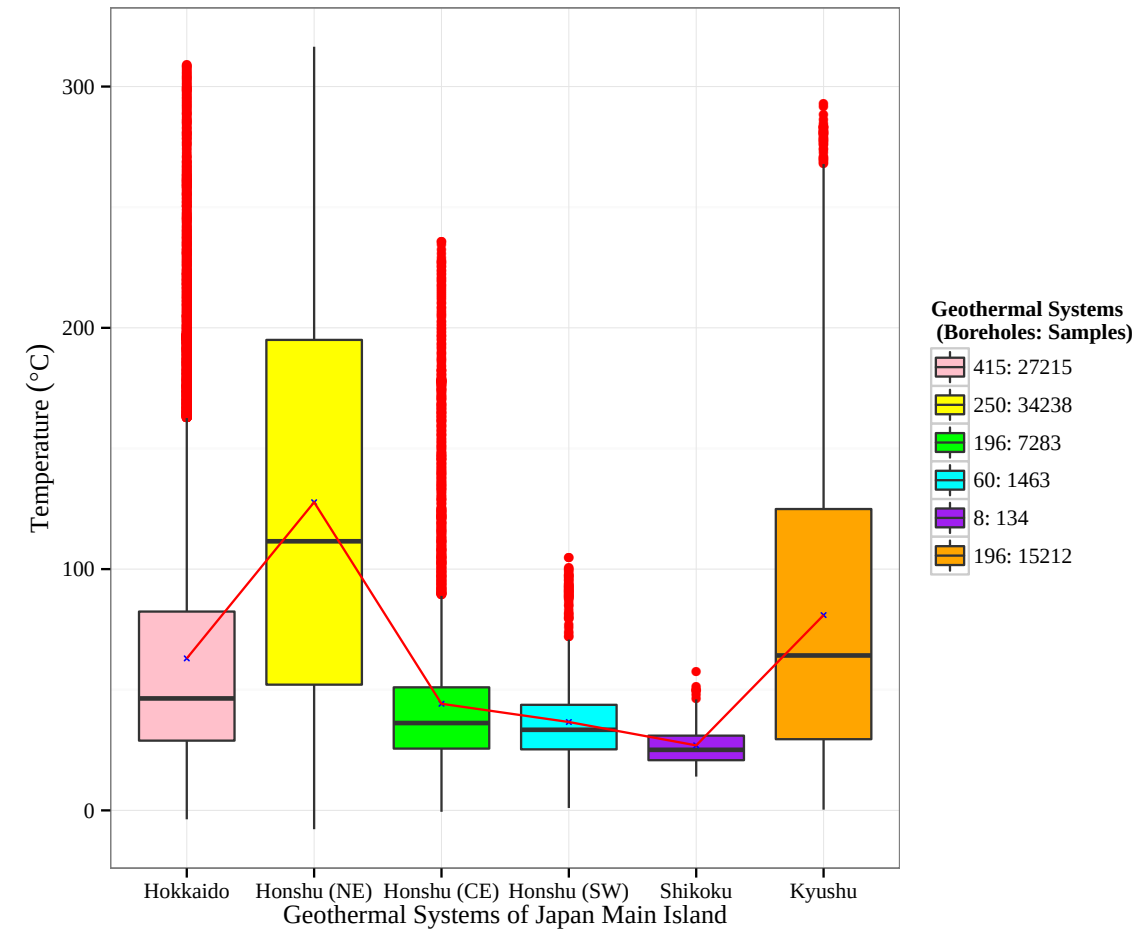


Fig. 6.4 Box-and-whisker plot of borehole data of each geothermal system in Japan.

is 415 and 27,215 respectively. Followed the Hokkaido, Northeast, Honshu, Kyushu, Center Honshu, Southwest Honshu, and Shikoku island are 250 and 34,328, 196 and 15,212, 196 and 7283, 60 and 1463, and 8 and 134 respectively. The details of each geothermal systems are summarized in 6.1. The distribution of the data inferred that the area have relatively more data are more motivated in geological surveys.

After remove the duplicated records in same site, Fig. 6.5 shows all the temperature profiles in Japan island, the regression line (the red line in 6.5) shows that the average thermal gradient is 95°C/km, which is three times higher than global average.

Table 6.1 Summary of Geothermal systems

Geothermal Systems	Hokkaido	Honshu (NE)	Honshu (CE)	Honshu (SW)	Shikoku	Kyushu
Regions (Prefectures)	Hokkaido (1)	Tohoku (6)	Kanto (7) Chubu (9)	Kansai (7) Chugoku (5)	Shikoku (4)	Kyushu (6)
Area(km ²)	83,460	63,860	92,470	64,680	18,790	39,600
Boreholes	434	271	223	64	8	214
Temperatures	28,485	34,512	8,020	1,517	134	15,948
Active Volcanoes	18	18	19	2	0	17
Hot Springs	2,220	3,870	7,800	3,100	570	9,640
GPP Units	1	9	1	0	0	11

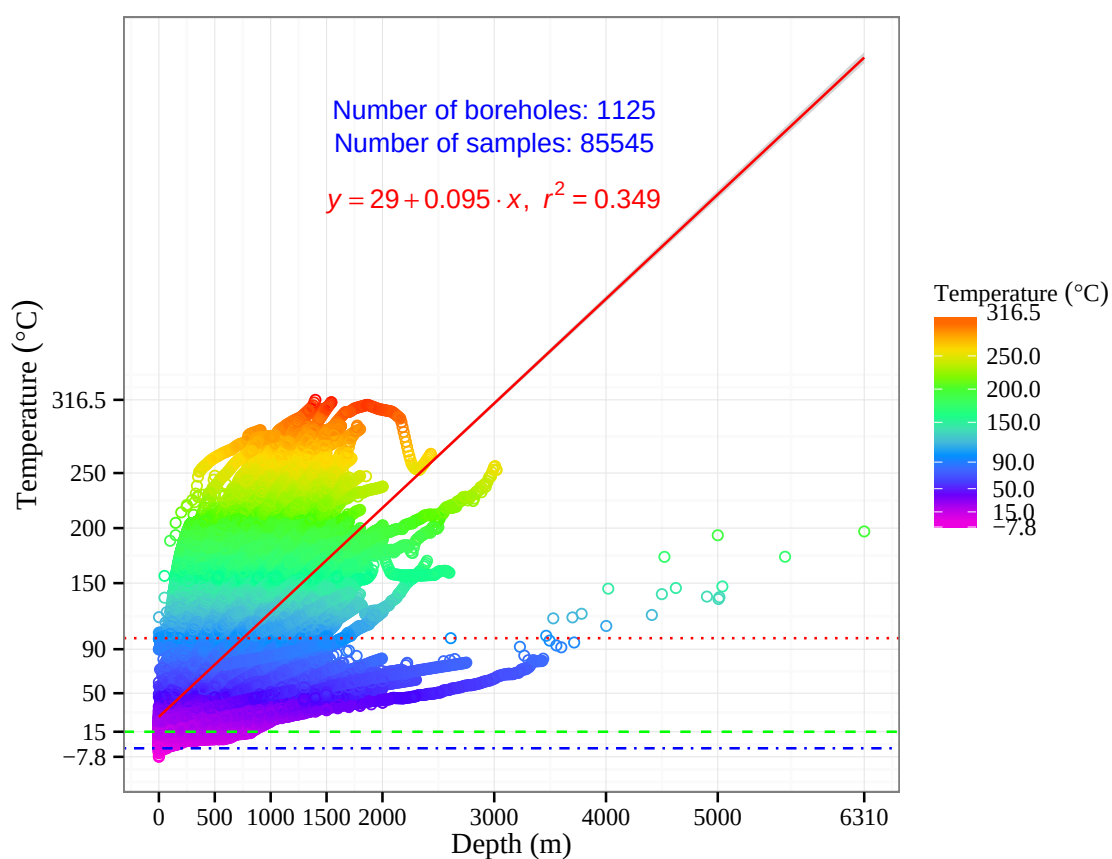


Fig. 6.5 Borehole temperature profiles of Japan. The red line denotes a linear regression of the relationship between temperature and depth and shows a geothermal gradient 95 °C/km. The dotted blue line shows 100 °C.

6.3 Methodologies

KED is suitable to produce a spatial model for the regionalized data having a significant spatial trend as the temperature logging data of this study. **KED** incorporates a local trend within the neighborhood search widow as a smooth varying function, which is usually polynomial function of the coordinates, and then, estimates the trend component within the window and a value at unsample point by simple kriging using the residuals of sample data. This residual is equal to the sample value minus the local mean in the window.

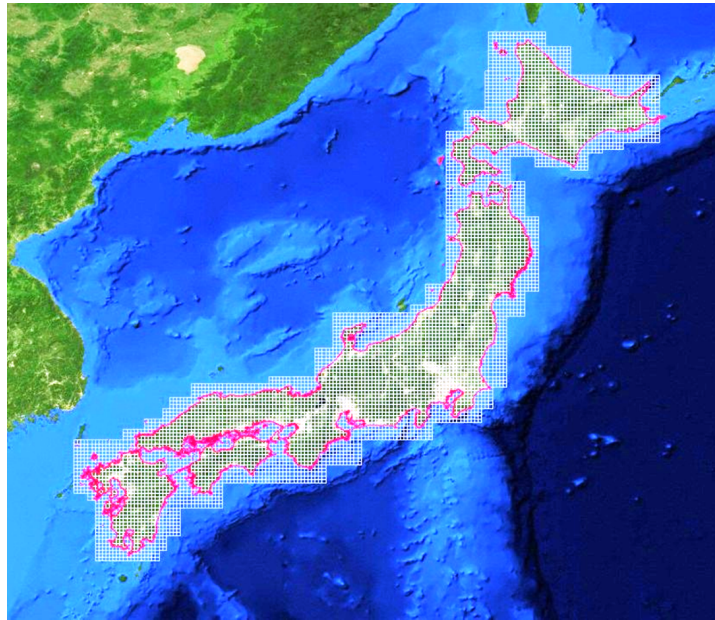


Fig. 6.6 Estimation grids of Japan with $1000 \times 1000 \times 100$ m resolution.

6.4 Results and Discussion

After calculation based on a $1000 \times 1000 \times 100$ m mesh (Fig. 6.6) and variogram (Fig. 6.7) in Japan main islands, Fig. 6.8 and Fig. 6.9 shows temperature distribution from 100 to 1000 m depth from the surface and 3D results respectively. The high temperature zones present in Eastern Hokkaido, Northeast Honshu, Center of Honshu and Southern Kyushu Island, especially in Northeast Honshu region, where the most concentrated high temperature zones are

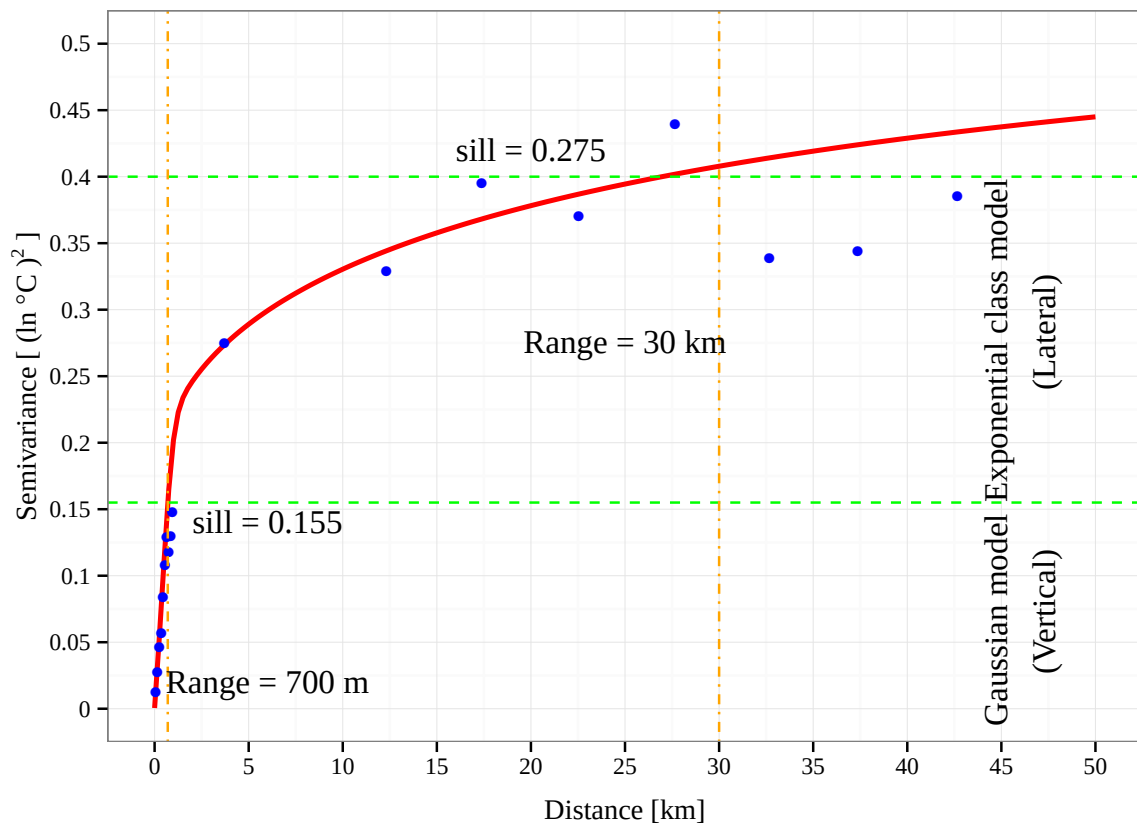


Fig. 6.7 Nested 3D variogram model (red curve) of Japan showing a mixture of two spatial correlation structures of temperatures data, short along the vertical direction and long along the lateral direction. The blue dots, green dashed lines, and orange dashed lines reflect experimental variograms, sills, and ranges, respectively.

characterized. On the other hand, low temperature zones are mainly around the Shikoku Island and Southwest Honshu, despite the fact that there are few volcanoes in Southwest Honshu region. The volcanic activity in these regions is related to the Philippine Sea Plate which subduct at the Nankai Trough. This part of the Philippine Sea Plate is younger and warmer than another part of the plate. Therefore, the slab is at shallow depths under the Southwest Japan Arc and the volcanic activity is dormant. Generally, deep temperature distribution is consistent with surface manifestations, especially active volcanoes. In Japan, the largest number of volcanoes and corresponding concentrated deep high temperature make the Northeast Honshu region be the most volume of volcanic products.

Fig. 6.9 shows how the high temperature zones related to distribution of active volcanoes and active faults. These distributions are concordant with the active and Quaternary volcanoes. There are high temperature zones unrelated to the volcanoes such as the southern top of Kii peninsula. Latent magma can be estimated under this peninsula associate with the subduction of the Philippine Sea Plate. Using the SST, heat energy can be calculated over Japan, which implies high recourse potential in the northern and southern Tohoku and middle Honshu regions. LST obtained by the set of MODIS scenery also reveals the high potentials of these regions.

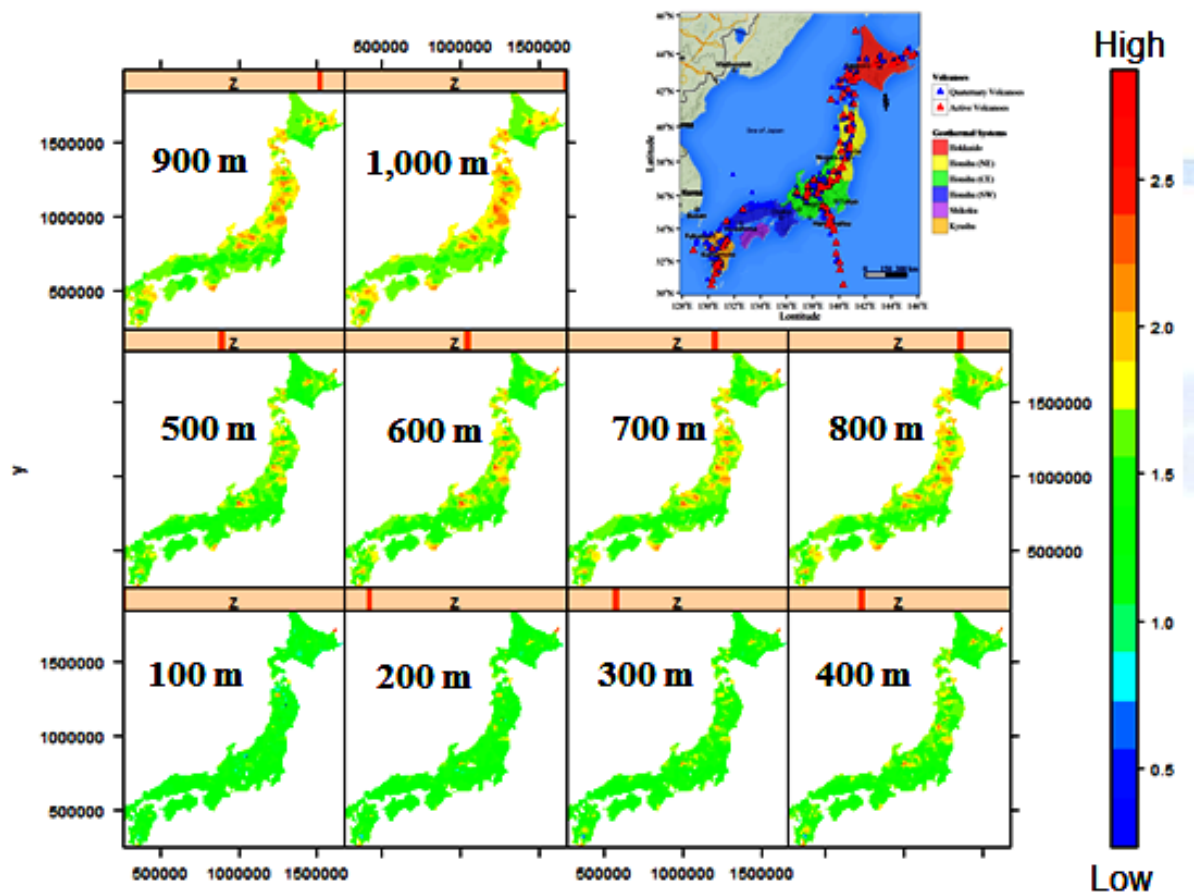


Fig. 6.8 Classification of geothermal resource by temperature, heat transfer type, depth and stress, and utilization.

6.5 Summary

I characterized the crustal temperature of the heat stored underground in different geothermal systems based on various geological structures, fault zones and volcanic zones, including Hokkaido, Northeast of Honshu, Center of Honshu, Southwest of Honshu, Shikoku, and Kyushu geothermal systems in Japan. The temperature distribution with a cell resolution of $1000 \times 1000 \times 100$ m was estimated using KED method in the 3D at the depth from 100 m of 1 km. Based on the result of the deep geothermal potentials, Eastern Hokkaido, Northeast Honshu, Center of Honshu and Southern Kyushu Island where further exploration and future exploitation of the geothermal resources is feasible in Japan were detected. Of these regions, the Northeast Honshu region owns the highest geothermal potential.

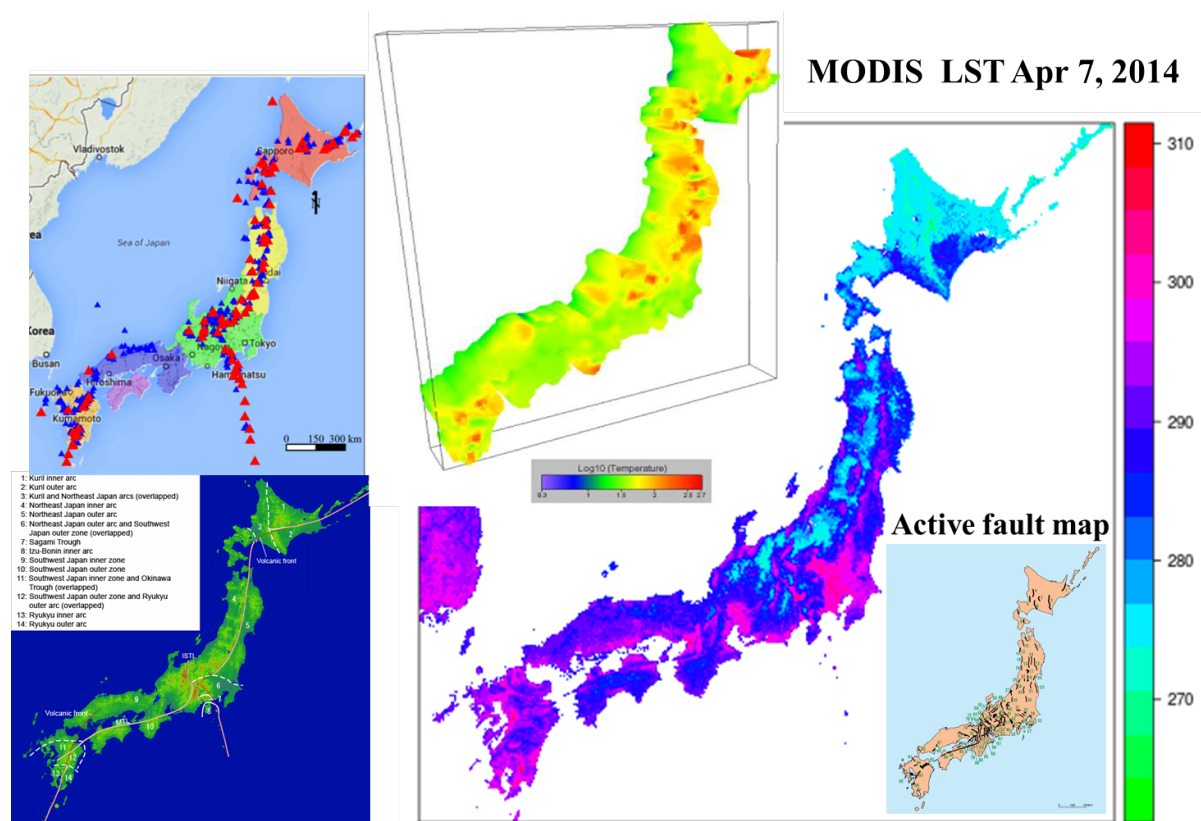


Fig. 6.9 3D modeling of geothermal distribution in Japan.

References

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- Kohl, T., N. Andenmatten, and L. Rybach (2003). “Geothermal resource mapping-example from northern Switzerland”. *Geothermics* 32, pp. 721–732. ISSN: 03756505. DOI: [10.1016/S0375-6505\(03\)00066-X](https://doi.org/10.1016/S0375-6505(03)00066-X).
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Chapter 7

Conclusions and Future Work

“A conclusion is simply the place where you got tired of thinking.”

Dan Chaon, *Stay Awake* (2012)

“All endings are also beginnings. We just don’t know it at the time.”

Mitch Albom, *The Five People You Meet In Heaven* (2003)

In this chapter, I firstly summarize the thesis. Main conclusions are given. Then some important future works and directions are proposed.

7.1 Conclusions

The whole dissertation is mainly about the following works: [Three Dimension \(3D\)](#) crustal temperature modeling over Japan for geothermal resource assessment; Accurate detection of geothermal energy resources by comparison and combination of [3D](#) modeling of well-logging temperature data with [Land Surface Temperature \(LST\)](#) data derived from [Thermal Infrared Remote sensing \(TIR\)](#); Identification of two thermal types of heat transfer from a set of temperature-logging profile dataset.

The history and development of geothermal energy resources in Japan was summarized. Although Japan ranked the third-rich in geothermal resources worldwide, only two percent of its potential is actually used for power generation, indicating large development room of geothermal energy utilization in Japan. Direct use in Japan is mainly for bathing (onsen). [Geothermal Heat Pumps \(GHP\)](#) would be a promising way to mitigate the [Urban Heat Island \(UHI\)](#) phenomenon.

Identification of thermal type of borehole, which is related to geothermal fluid, is essential to geothermal exploration and reservoir mapping because thermal conductivity in water is relatively lower than in average rock materials. The last main work focused on identifying the two types of heat transfer in the crust, conductive and convective, from a set of temperature-logging dataset using coefficient of determination method. Threshold of 0.9 was finally chosen to discriminate the two thermal types. It was proved by the calculation that coefficient of determination was a proper index to identify conductive and convective types and be available to [3D](#) temperature modeling.

A case study in Hokkaido, northern Japan were conducted to implement the accurate detection of geothermal energy resources by comparison and combination of 3D modeling of well-logging temperature data with Land surface temperature data derived from [TIR](#). A set of the 28,476 well-logging temperature datapoints collected from 433 sites and 13 Landsat 8 [Thermal InfraRed Sensor \(TIRS\)](#) images were used to clarify the extensive variability of temperatures in the upper crust and on the surface. The [Subsurface Temperature \(SST\)](#) model was constructed using the dataset and a geostatistical method, [Kriging with External Drift or trend \(KED\)](#) while the [LST](#) map was first produced using the [Land Surface Emissivity \(LSE\)](#) based universal algorithm by Artis et al. (Artis et al., 1982), and then transformed into the residual form by subtracting the scene average temperature to detect local thermal anomalies. Remarkable features were detected from the [SST](#) model by [KED](#); specifically, high temperature zones were

mostly located in the western region and a part of the eastern region in accordance with the distribution of Quaternary volcanoes and high heat flow, while the central region was dominated by low temperatures due to the thick cover of sedimentary rocks. Although **LST** is mostly controlled by **Land-Use and Land-Cover (LULC)**, such as urban areas and topography, high temperature anomaly zones were detected in the high **SST** areas. These findings demonstrate the effectiveness of the combination of subsurface and surface temperatures using geostatistical spatial modeling and **TIRS** remote sensing for identification of zones with high potential for geothermal resources.

Based on various geological structures, fault zones and volcanic zones, the crustal temperature of the heat stored underground in different geothermal systems was characterized, including Hokkaido, Northeast of Honshu, Center of Honshu, Southwest of Honshu, Shikoku, and Kyushu geothermal systems in Japan. The temperature distribution with a cell resolution of $1000 \times 1000 \times 100$ m was estimated using **KED** method in the three dimension at the depth from 100 m to 1 km. According to the results of the deep geothermal potentials, Eastern Hokkaido, Northeast Honshu, Center of Honshu and Southern Kyushu Island where further exploration and future exploitation of the geothermal resources is feasible in Japan were detected. Of these regions, the Northeast Honshu region owns the highest geothermal potential.

7.2 Future Work

Future work will be emphasized on update assessment of geothermal in Japan by combining **LST**, well-logging dataset, heat flow, conductivity, thermal gradient, and conduction and convection. The main future works and directions are:

- Improving the accuracy of the **3D SST** modeling using different trends (linear or quadratic) in **3D** kriging based on identification of heat transfer type and combining with numerical modeling.

- Improving the spatial and temporal resolution of [LST](#) through multiple spatiotemporal [LST](#) analysis, Landsat and [MODerate resolution Imaging Spectroradiometer \(MODIS\)](#) fusing, and cross validation with [MODIS](#) time series and [Advanced Spaceborne Thermal Emission and Reflection radiometer \(ASTER\)](#) global emissivity dataset.
- Considering the problem of non-geometry anisotropy and influence of [UHI](#) and [LULC](#); using night data from [MODIS](#) to decrease this kind of the influence and to improve the detection of geothermal structures.
- Continuing to develop and document the two R packages (TIR and GeothermaR) for geothermal research and development.
- Contributing this research to [Science and Technology Research Partnership for Sustainable Development \(SATREPS\)](#) geothermal project: “Technology development of steam-spot detection and sustainable resource use for large enhancement of geothermal power generation in Indonesia”.

References

- Artis, D. A. and W. H. Carnahan (1982). “Survey of Emissivity Variability in Thennography of Urban Areas”. 329, pp. 313–329.

R Packages and Codes

“That’s the thing about people who think they hate computers. What they really hate is lousy programmers.”

Larry Niven, *science fiction writer*

R is a very powerful and popular free and open source software for statistics, data analysis, graphics and programming. Most part of the data processing and analysis in this dissertation was implemented using R.

.1 List of main packages used in the thesis and basic settings

Except base and default suggested R packages, A lot of R packages especially in [Comprehensive R Archive Network \(CRAN\)](#) task view: Analysis of Spatial Data were implemented.

List of packages and basic setups in “phdRsettings.R”

```
#' @usage source("~/SparkleShare/Rprofile/R/Rsettings/phdRsettings.R")
# rm(list=ls())
# library(plotly)
library(sp)
library(gstat)
library(rgdal)
library(gdalUtils)
library(maptools)
library(raster)
library(plotKML)
library(plyr)
library(rgeos)
library(RSAGA)
### Graph
library(grid)
library(gridExtra)
```

```

library(ggplot2)
library(gtable)
library(ggmap)
library(rasterVis)
library(lattice)
library(latticeExtra)
### packages
source("~/SparkleShare/Rprofile/R/RprofilesAuto/sourceDir.R")
sourceDir("~/SparkleShare/Rprofile/R/RprofilesAuto")
sourceDir("~/SparkleShare/TIR/R/")
sourceDir("~/SparkleShare/rLandsat8/src/main/R/rLandsat8/R")
sourceDir("~/SparkleShare/geothermaR/R/")
## Options
if(.Platform$OS.type == "windows"){
  windowsFonts(Times=windowsFont("TT_Times_New_Roman"))
  windowsFonts(times=windowsFont("TT_Times_New_Roman"))
}

### RasterOptions
rasterOptions(todisk = FALSE)
rasterOptions(chunksize = 5e+08, maxmemory = 1e+09)
#rasterOptions(tmpdir = dir.tmp)
raster::removeTmpFiles(h = 1)
raster
theme_set(theme_bw(base_size = 12, base_family = "Times"))
gc()
### Colors
rainbow.GR <- colorRampPalette(rainbow(n = 255, start = 2/6))
ge.rainbow <- grDevices::colorRampPalette(c("purple", "blue", "cyan", "green", "
  yellow", "orange", "red"))
oceColorsJet <- function (n)
{
  if (missing(n) || n <= 0)
    colorRampPalette(c("#00007F", "blue", "#007FFF", "cyan",
      "#7FFF7F", "yellow", "#FF7F00", "red", "#7F0000"))
  else {
    colorRampPalette(c("#00007F", "blue", "#007FFF", "cyan",
      "#7FFF7F", "yellow", "#FF7F00", "red", "#7F0000"))(n)
  }
}

# Extent of Study area of Japan in the PhD dissertation
xlimJP <- c(128.5, 146.5)
ylimJP <- c(30.2, 45.8)
centerJP <- c(137.5, 38)

# Coordinate Reference Systems of Japan
## Geographic Coordinate Reference Systems
#tokyoGRS <- "+init=epsg:4301"
tokyoGRS <- "+proj=longlat+ellps=bessel+no_defs"
#wgs84GRS <- "+init=epsg:4326"
wgs84GRS <- "+proj=longlat+ellps=WGS84+datum=WGS84+no_defs+towgs84=0,0,0"
#jgd2000GRS <- "+init=epsg:4612"
jgd2000GRS <- "+proj=longlat+ellps=GRS80+towgs84=0,0,0,0,0,0,0,0+no_defs"

```



```
## Projected Coordinate Reference Systems
lccBessel <- "+proj=lcc+lat_1=32.8+lat_2=43.2+lat_0=38+lon_0=137.5+x_
0=1000000+y_0=1000000+ellps=bessel+towgs84
=-146.414,507.337,680.507,0,0,0,0+units=m+no_defs"
## change the datum to WGS84
lccWgs84 <- "+proj=lcc+lat_1=32.8+lat_2=43.2+lat_0=38+lon_0=137.5+x_
0=1000000+y_0=1000000+datum=WGS84+units=m+no_defs"
# +ellps=WGS84 +towgs84=0,0,0
```

.2 List of functions developed in the dissertation

.2.1 Main geothermaR functions: <https://github.com/bwtian/geothermaR>

```
ge.crsTransform <- function(df, x, y, xName, yName, fromCRS, toCRS)
#transfer CRS in a dataframe fromat, x, y will be repaced in data.frame
{
  df$x <- df[,which(colnames(df) == as.character(substitute(x)))]
  df$y <- df[,which(colnames(df) == as.character(substitute(y)))]
  library(sp)
  library(rgdal)
  coordinates(df) <- c("x", "y")
  proj4string(df) <- CRS(fromCRS)
  df <- spTransform(df, CRS(toCRS))
  df <- as.data.frame(df)
  names(df)[which(names(df) == "x")] <- as.character(substitute(xName))
  names(df)[which(names(df) == "y")] <- as.character(substitute(yName))
  return(df)
}

ge.cv <- function(cv, response){
  ### Check CrossValidation
  ### mean error, ideally should be 0
  me0 <- mean(cv$residual)
  me00 <- mean(cv$residual^2)

  rmse0 <- sqrt(mean(cv$residual^2))
  #rmse0 <- rmse0/sd(response)
  ### correlation observed and predicted, ideally 1
  #me1 <- mean(cv$residual^2/cv$var1.var)
  cor1 <- cor(cv$observed, cv$observed - cv$residual)
  ### correlation predicted data and residual
  cor0 <- cor(cv$observed - cv$residual, cv$residual)
  ### Results
  results <- c(me0, me00, rmse0, rmse0, cor1, cor0)
  names(results) <- c("Mean_error=0", "Mean_suqred_error=0", "rmse=0", "rmse0=0",
"correlation=1", "correlation=0")
  return(results)
}
```

```

ge.df2collars <- function(ID, Easting, Northing, Elevation, Azimuth = 0, Dip = 0,
  Depth) {
  ID <- ID
  well <- as.data.frame(ID)
  well$Easting <- Easting
  well$Northing <- Northing
  well$Elevation <- Elevation
  well$Azimuth <- Azimuth
  well$Dip <- Dip
  well$Depth <- Depth
  well[sort(well$ID),]
  return(well)
}

ge.df2csv <- function(df) {
  ## write data.frame as csv and rds file into data folder using df name itself
  now <- format(Sys.time(), "_%y%m%d_%H%M%S")
  csvName <- paste(deparse(substitute(df)), now, ".csv", sep = "")
  rdsName <- paste(deparse(substitute(df)), now, ".Rds", sep = "")
  write.table(df, csvName, sep = ",", quote = F, row.names = F)
  saveRDS(df, rdsName)
}

ge.df2spwgs84 <- function(df, x, y) {
  # spatialize a data frame to spdf
  d <- df
  d$x <- d[,which(colnames(d) == as.character(substitute(x)))]
  d$y <- d[,which(colnames(d) == as.character(substitute(y)))]
  wgs84GRS <- "+proj=longlat+ellps=WGS84+datum=WGS84+no_defs"
  coords <- d[, c("x", "y")]
  m <- as.matrix(coords) #sp need numeric matrix
  mode(m) <- "numeric"
  sp <- sp::SpatialPoints(m, proj4string = sp::CRS(wgs84GRS))
  spdf <- sp::SpatialPointsDataFrame(m, data = d, proj4string=sp::CRS(wgs84GRS))
  return(spdf)
}

ge.df2trajectories <- function(ID, MD, Azimuth = 0, Inclination = 0) {
  ID <- ID
  well <- as.data.frame(ID)
  well$MD <- MD
  well$Azimuth <- Azimuth
  well$Inclination <- Inclination
  well[sort(well$ID),]
  return(well)
}

ge.df2voxlerSamples <- function(ID, From, To, V1, ...) {
  ID <- ID
  well <- as.data.frame(ID)
  well$From <- From
  well$To <- To
  well$V1 <- V1
  well[sort(well$ID),]
}

```

```

    return(well)
}

ge.conAreaSPDF <- function(SPDF, area) {
  ### Extract Polygons(Layer) by Area to SPDF1
  crs <- sp::proj4string(SPDF)
  areas_Polygons <- sapply(SPDF@polygons, function(Polygons) Polygons@area)
  ids_polygons <- which(areas_Polygons >= area)
  SPDF1 <- SPDF[ids_polygons,]
}

ge.LargestPolys <- function(SPDF, Polygon = FALSE, Polygons = FALSE) {
  ### TODO: lvl = match.type("Polygons", "Polygon", "polygons")
  ### Extract Largest Polygons(Layer) from SPDF to SPDF1 08-14
  if (class(SPDF)[1] != "SpatialPolygonsDataFrame")
    stop("Must be a SpatialPolygonsDataFrame object")
  crs <- sp::proj4string(SPDF)
  areas_Polygons <- sapply(SPDF@polygons, function(Polygons) Polygons@area)
  id_Polygons <- which.max(areas_Polygons)
  SPDF1 <- SPDF[id_Polygons,]
  ### Extract Largest Polygon to SPDF2
  area_fun <- function(polygons) {
    sapply(polygons@Polygons, function(Polygon) Polygon@area)
  }
  areas_Polygon <- lapply(SPDF@polygons, area_fun)
  mx_Polygons <- areas_Polygon[[id_Polygons]]
  id_Polygon <- which.max(mx_Polygons)
  mx_Polygon <- SPDF@polygons[[id_Polygons]]@Polygons[[id_Polygon]]
  toPolygons <- sp::Polygons(list(mx_Polygon), id_Polygon) #ID for row.names = 1
  toSP <- sp::SpatialPolygons(list(toPolygons))
  SPDF2 <- as(toSP, "SpatialPolygonsDataFrame")
  ### Extract Largest Polygon in each Polygons to SPDF3
  ids_mxpols <- lapply(areas_Polygon, function(x) which.max(x))
  Polygons_l <- list()
  for (i in 1:length(ids_mxpols)) {
    Polygons_l[[i]] <- SPDF@polygons[[i]]@Polygons[[ids_mxpols[[i]]]]
  }
  toPolygons <- sp::Polygons(Polygons_l, 1) #ID for row.names = 1
  toSP <- sp::SpatialPolygons(list(toPolygons))
  SPDF3 <- as(toSP, "SpatialPolygonsDataFrame")
  sp::proj4string(SPDF1) <- crs
  sp::proj4string(SPDF2) <- crs
  sp::proj4string(SPDF3) <- crs
  if (Polygons) {
    return(SPDF3)
  } else if (Polygon) {
    return(SPDF2)
  } else {
    return(SPDF1)
  }
}

ge.geoCode <- function(nameLst) {
  # get longitude, latitude, and Name of given place

```

```

lonlata <- ggmap::geocode(nameLst, output = "latlona")
names <- do.call("rbind", strsplit(lonlata[,3], ","))
name <- Hmisc::capitalize(names[,1])
lonlatn <- cbind(lonlata[,c(1,2)], name)
return(lonlatn)
}

ge.ggsave <- function(gg, scale = 1, dpi = 300, ...) {
  now <- format(Sys.time(), "_%y%m%d_%H%M%S")
  fileName <- deparse(substitute(gg))
  pngName <- paste0(fileName, now, ".png")
  tifName <- paste0(fileName, now, ".tiff")
  pdfName <- paste0(fileName, now, ".pdf")
  ggsave(pdfName, plot = gg, scale = scale, dpi = dpi)
  ggsave(pngName, plot = gg, scale = scale, dpi = dpi)
  ggsave(tifName, plot = gg, scale = scale, dpi = dpi)
}

ge.heat <- function(p, a, d, t1, t0) {
  q <- p * a * d * (t1 - t0)
}

ge.kml2spdf <- function(kml, name = FALSE){
  ### Extracting Information from Kml to Dataframe [2014-06-26 Thu]
  cha <- readLines(kml)
  doc <- XML::htmlParse(cha) # xmlParse not work here!!!
  nod <- XML::xpathApply(doc, "//description")
  des_d <- as.data.frame(t(sapply(nod, function(x)unname(XML::xmlSApply(x, XML::
    xmlValue))))))
  xy_l <- XML::xpathSApply(doc, "//coordinates", XML::xmlValue)
  xy_d <- as.data.frame(do.call("rbind", strsplit(xy_l,",")))
  names(xy_d) <- c("lon","lat")
  if (name) {
    ### for same bad structure of KML
    name_d <- as.data.frame(XML::xpathSApply(doc, "//name", XML::xmlValue))
    names(name_d) <- "Name"
    kml_d <- cbind(name_d, xy_d, des_d)}
  else
    kml_d <- cbind(xy_d, des_d)
  kml_d <- kml_d[, colSums(kml_d != "") != 0] ## Clear Empty Column
  coords <- kml_d[, c("lon","lat")]
  coords_m <- as.matrix(coords) #sp need numeric matrix
  mode(coords_m) <- "numeric"
  options(digits=15) #based on origin data
  kml_sp <- sp::SpatialPoints(coords_m, proj4string = sp::CRS(wgs84GRS))
  kml_spdf <- sp::SpatialPointsDataFrame(coords_m, data =kml_d, proj4string=sp::
    CRS(wgs84GRS))
  return(kml_spdf)
  #phd.saveshp.geo(kml_spdf)
}

ge.lm2df <- function(lm) {
  #wrap a lm resuts to data frame format
  cf <- coef(lm)
  tinfo <- summary(lm)$coefficients[2, c(2, 4)]

```

```

r2 <- summary(lm)$r.squared
data.frame(intercept = cf[1], slope = cf[2], n = length(resid(lm)),
  slope.se = tinfo[1], pval = tinfo[2], Rsq = r2)
}

ge.nearest <- function(df, x, y, i = 100){
  if(require(plyr)){
    nearest <- function(x,y = 100) {
      x <- as.numeric(x)
      if(require(plyr)){
        x[which.min(abs(x - round_any(x,y)))]
      }
    }
    df$y <-
    by <- by(df$x, df$y, nearest)
    suber <- as.data.frame(cbind(by))
    names(suber) <- as.character(y)
    mode(df$x) <- mode(suber$x)
    out <- match_df(df, suber)
    return(out)
  }
}

ge.slice100m <- function(df, toslice, na.omit = FALSE) {
  ## creat slice factors
  intervals <- as.numeric()
  ## TODO power <- log(10,int)
  for (i in 1:length(toslice)) {
    if(round(toslice[i],-2) == round(toslice[i],-1)) {
      ##intervals[i] <- round(toslice[i],-2)/%int
      intervals[i] <- round(toslice[i],-2)
    } else {
      intervals[i] <- NA
    }
  }
  df$slice <- intervals
  if(na.omit){
    data <- na.omit(df)
  }

  ### for voxler soft export
  #data.d$from <- data.d$slice - 50
  #data.d$to <- data.d$slice + 50
  #return(data.d)
  return(df)
}

ge.sp2shpGeo <- function(obj) {
  ## write sp object as shp, kml rds and csv file
  now <- format(Sys.time(), "%Y%m%d_%H%M%S")
  csvName <- paste0(deparse(substitute(obj)), now, ".csv")
  rdsName <- paste0(deparse(substitute(obj)), now, ".Rds")
  pngName <- paste0(deparse(substitute(obj)), now, ".png")
  shpName <- paste0(deparse(substitute(obj)), now)

```

```

kmlName <- paste0(deparse(substitute(obj)), now)
kmlDsn <- paste0("./", kmlName, ".kml")
write.table(as.data.frame(obj), csvName, sep = ",", quote = F, row.names = F)
saveRDS(obj, rdsName)
png(pngName); plot(obj); dev.off()
if(require(rgdal)){
  writeOGR(obj, dsn = '.', layer = shpName, driver = "ESRI_Shapefile")
  writeOGR(obj, dsn = kmlDsn, layer = kmlName, driver = "KML")
}
}

ge.sp2shpPrj <- function(obj) {
  ## write sp objects as shp, rds and csv file
  now <- format(Sys.time(), "%Y%m%d_%H%M%S")
  csvName <- paste(deparse(substitute(obj)), now, ".csv", sep = "")
  rdsName <- paste(deparse(substitute(obj)), now, ".Rds", sep = "")
  shpName <- paste(deparse(substitute(obj)), now, sep = "")
  write.table(as.data.frame(obj), csvName, sep = ",", quote = F, row.names = F)
  saveRDS(obj, rdsName)
  if(require(rgdal)){
    writeOGR(obj, dsn = '.', layer = shpName, driver = "ESRI_Shapefile")
  }
}

ge.sp2spdf <- function(sp){
  sp <- as(grid, "SpatialPoints")
  df <- data.frame(as.factor(1:length(sp)))
  spdf <- sp::SpatialPointsDataFrame(sp, df)
}

ge.sp2spdf <- function(sp){
  sp <- as(grid, "SpatialPoints")
  df <- data.frame(as.factor(1:length(sp)))
  spdf <- sp::SpatialPointsDataFrame(sp, df)
}

ge.SP2F2grid <- function(SP2F,x, y = x, type = "regular"){
  sp <- sp::spsample(SP2F,type = type, cellsize = c(x,y), offset =c(0.5, 0.5))
  df <- data.frame(id = as.factor(1:length(sp)))
  spdf <- sp::SpatialPointsDataFrame(sp, data = df)
}

ge.spdf2SP2F <- function(spdf) {
  grd <- spdf
  sp::gridded(grd) <- TRUE
  grd_SP2F <- as(grd, "SpatialPolygonsDataFrame")
  return(grd_SP2F)
}

ge.splitPoly <- function(line,poly){
  x <- gIntersection(line, poly)
  bx <- gBuffer(x, width = 0.000001)
  dx <- gDifference(poly, bx)
}

ge.urlTable <- function(url, table = 1 ) {

```

```

## scrape the table to dataframe from a url website
if(!require(XML)){
  installed.packages("XML")
} else {
  url.doc <- htmlParse(url)
  url.l <- readHTMLTable(url.doc)
  url.d <- url.l[[table]]
}
return(url.d)
}

ge.xy2bboxSPDF <- function(xmin,xmax,ymin,ymax,crs = NA){
  ### Make a bbox rect SPDF from LL and TR point.
  xmin <- as.numeric(xmin)
  xmax <- as.numeric(xmax)
  ymin <- as.numeric(ymin)
  ymax <- as.numeric(ymax)
  Polygon <- sp::Polygon(cbind(c(xmin, xmin, xmax, xmax, xmin),
    c(ymin, ymax, ymax, ymin, ymin)))
  Polygons <- sp::Polygons(list(Polygon), 1) #ID for row.names = 1
  SP <- sp::SpatialPolygons(list(Polygons))
  data_d <- data.frame(name = "bbox", row.names= row.names(Polygons))
  SPDF <- sp::SpatialPolygonsDataFrame(SP, data = data_d)
  sp::proj4string(SPDF) <- crs
  return(SPDF)
}

ge.xy2fishnet <- function(x1,x2,y1,y2,rx=1000,ry=rx) {
  x.range.v <- seq(as.numeric(x1),as.numeric(x2),by = rx)
  y.range.v <- seq(as.numeric(y1),as.numeric(y2),by = ry)
  grid.m <- outer(x.range.v, y.range.v, paste, sep = ",")
  grid.v <- as.vector(grid.m)
  grid.d <- as.data.frame(grid.v)
  fishnet.d <- data.frame(do.call('rbind', strsplit(as.character(grid.d[,1]), ','),
    fixed=TRUE)))
  colnames(fishnet.d) <- c("x","y")
}

```

.2.2 Main TIR functions: <https://github.com/bwtian/TIR>

```

#' Read NASA ASTER Global Emissivity Database (ASTER GED) Binary Datasets
#' @export
#' @details Layers: 19
#' Resolution: 100 m * 100 m
#' Dimensions: 1000*1000*19
#' NA: -9999
#' @param emiB10m layer1 is Emissivity mean of Band10 scaled by 1000
#' @param emiB11m layer2 is Emissivity mean of Band11 scaled by 1000
#' @param emiB12m layer3 is Emissivity mean of Band12 scaled by 1000
#' @param emiB13m layer4 is Emissivity mean of Band13 scaled by 1000
#' @param emiB14m layer5 is Emissivity mean of Band14 scaled by 1000
#' @param emiB10sd layer6 is Emissivity sdev of Band10 scaled by 10000
#' @param emiB11sd layer7 is Emissivity sdev of Band11 scaled by 10000

```

```

#' @param emiB12sd layer8 is Emissivity sdev of Band12 scaled by 10000
#' @param emiB13sd layer9 is Emissivity sdev of Band13 scaled by 10000
#' @param emiB14sd layer10 is Emissivity sdev of Band14 scaled by 10000
#' @param LSTm layer11 is LST mean scaled by 100, Unit Kelvin(K)
#' @param LSTsd layer12 is LST sdev scaled by 100, Unit Kelvin(K)
#' @param NDVIm layer13 is NDVI mean scaled by 100 at TOA
#' @param NDVIsd layer14 is NDVI sdev scaled by 100 at TOA
#' @param Water layer15 is Land-Water Map
#' @param Obs layer16 is Observations, Images used
#' @param Lat layer17 is Latitude scaled by 1000
#' @param Lon layer18 is Longitude scaled by 1000
#' @param GDEM layer19 is ASTER Global DEM
#' @param bins A list of Binary files need to read
#' @return A list of dataframes

readAG100B <- function(bins){
  out <- list()
  for (i in bins) {
    toRead <- file(i, "rb")
    data.v <- readBin(toRead, integer(), size = 4, n = 19000000)
    close(toRead)
    layer.l <- split(data.v, ceiling(seq_along(data.v)/1000000))
    layer.d <- as.data.frame(layer.l)
    layer.d[layer.d == -9999] <- NA
    #layer.m <- as.matrix(layer.d)
    # scales <- c(1000, 1000, 1000, 1000, 1000,
    # 10000, 10000, 10000, 10000, 10000,
    # 100, 100, 100, 100,
    # 1, 1, 1000, 1000, 1)
    #layer.ok <- mapply("/", layer.d, scales)
    #layer.ok <- layer.d/scales
    #layer.df <- as.data.frame(layer.ok)
    layer.df <- as.data.frame(layer.d)
    colnames(layer.df) <- c("emiB10m", "emiB11m", "emiB12m",
    "emiB13m", "emiB14m", "emiB10sd",
    "emiB11sd", "emiB12sd", "emiB13sd",
    "emiB14sd", "LSTm", "LSTsd", "NDVIm",
    "NDVIsd", "Water", "Obs",
    "Lat", "Lon", "GDEM")
    idx <- seq_along(bins)[sapply(bins, function(x) i %in% x)]
    out[[idx]] <- layer.df
  }
  return(out)
}

#' creates a raster with the TOA radiance
#'
#' @description Creates a raster with the TOA radiance
#'
#' @param landsat8 list returned by rLandsat8::ReadLandsat8
#' @param band Landsat 11 bandname (one of "aerosol", "blue", "green", "red", "
nir", "swir1", "swir2", "panchromatic", "cirrus", "tirs1", "tirs2"
#' @return TOA Radiance raster
#' @examples \dontrun{

```



```

#’ ls8 <- ReadLandsat8("LC81880342014174LGN00")
#’ r <- ToTOARadiance(ls8, "red")
#’ }
#’ @note code form rLandsat8
#’ @export
#’ @import raster

ToTOARadiance <- function(landsat8, band) {

  bandnames <-c("aerosol", "blue", "green", "red",
               "nir", "swir1", "swir2",
               "panchromatic",
               "cirrus",
               "tirs1", "tirs2")

  allowedbands <- bandnames

  if (!band %in% allowedbands)
  {
    stop(paste(band, "band_not_allowed"))
  }

  idx <- seq_along(bandnames)[sapply(bandnames, function(x) band %in% x)]

  ml <- as.numeric(landsat8$metadata[[paste0("radiance_mult_band_",idx)]])
  al <- as.numeric(landsat8$metadata[[paste0("radiance_add_band_",idx)]])

  TOArad <- landsat8$band[[band]] * ml + al

  return(TOArad)
}

## Add new
18.DNtoTOARadiance <- function(idenfier){
  bandnames <-c("aerosol", "blue", "green", "red",
               "nir", "swir1", "swir2",
               "panchromatic",
               "cirrus",
               "tirs1", "tirs2")

  sapply(bandnames, function(i){ToTOARadiance(idenfier, i)})
}
#’ Get Google Map using ggmap function
#’
#’ @param lon Longitude
#’ @param lat Latitude
#’ @param zoom Zoom
#’ @param prefix Prefix for the data saved
#’ @import ggmap
#’ @export
#’ @author Bingwei Tian
#’ @details
#’ This function will get the Google map from the

```

```

#’
#’ @importFrom ggmap get_googlemap
#’ @export
getGoogleMap <- function(lon, lat, zoom, prefix = "google"){
  ### ggmap 4 type of google map and save to Rds 08-15
  require(ggmap)
  x <- deparse(substitute(lon))
  y <- deparse(substitute(lat))
  z <- deparse(substitute(zoom))
  now <- format(Sys.time(), "_%y%m%d_%H%M")
  for (i in c("terrain", "satellite", "roadmap", "hybrid")){
    fileName <- paste0(prefix, "_google_", i, "_", x, "_", y, "_zoom", z, now, ".Rds")
    file <- get_googlemap(center = c(lon = lon, lat = lat), zoom = zoom,
      maptype = i, filename = fileName)
    saveRDS(file, file = fileName)
  }
}

#’ Reads a Landsat 8 product
#’ @description Reads a Landsat 8 product
#’
#’ @param product name of the product, e.g. LC80522102014165LGN00. It must be in
#’ the working directory
#’ @return list with metadata and raster bands
#’ @examples \dontrun{
#’   ReadLandsat8("LC80522102014165LGN00")
#’ }
#’
#’ @note ReadLandsat8 Function originlly from Package rLandsat8
#’
#’ @export
#’ @import raster

ReadLandsat8 <- function(product) {

  raster.files <- list("aerosol"="file_name_band_1",
    "blue"="file_name_band_2",
    "green"="file_name_band_3",
    "red"="file_name_band_4",
    "nir"="file_name_band_5",
    "swir1"="file_name_band_6",
    "swir2"="file_name_band_7",
    "panchromatic"="file_name_band_8",
    "cirrus"="file_name_band_9",
    "tirs1"="file_name_band_10",
    "tirs2"="file_name_band_11"
  )

  meta.file <- paste0(product, "/", product, "_MTL.txt")

  if (!file.exists(meta.file))
    stop(paste(meta.file, "file not found."))

  textLines <- readLines(meta.file)

```

```

counts <- count.fields(textConnection(textLines), sep="=")

met <- read.table(text=textLines[counts == 2], as.is=TRUE, header=FALSE, sep="=
", strip.white=TRUE, stringsAsFactors=FALSE)

met <- read.table(text=textLines[counts == 2], as.is=TRUE, header=FALSE, sep="=
", strip.white=TRUE, stringsAsFactors=FALSE, row.names = NULL, col.names=c("
name", "value"))

met <- met[!met$name == "GROUP", ]
met <- met[!met$name == "END_GROUP", ]
rownames(met) <- tolower(met[, "name"])
met[, "name"] <- NULL

met <- as.list(as.data.frame(t(met), stringsAsFactors=FALSE))

bands=lapply(raster.files, function(x) {
  r <- raster(paste0(product, "/", met[[x]]))
  r@title <- names(raster.files)[seq_along(raster.files)[sapply(raster.files,
    function(a) x %in% a)]]
  NAvalue(r) <- 0
  return(r)
})

return(list(metadata=met,
band=bands)
)
}
require(raster)
rs.readL8 <- ReadLandsat8

rs.modis2png <- function(dir = getwd()){
  inRaster <- list.files(path = getwd(), pattern = ".tif$", full.names = TRUE,
    recursive = TRUE)
  for (i in inRaster) {
    outName <- gsub("\\\\.tif", "\\\\.tif.png", i)
    r <- raster(i) *0.02
    #mr <- mask(r, m)
    cols = bpy.colors(30)
    png(filename = outName)
    #plot(r)
    pict <- spplot(r, col.regions = cols )
    print(pict)
    dev.off()
  }
}

tir.modis2png <- function(){
  files <- list.files(path=getwd(), pattern="*.tif", all.files=T, full.names=T)
  # for loop for processing all the image in tif files
  # infile is a file form tif files, outfile is a output file
  for (infile in files)
  {

```

```

#gsub to rename the infile to outfile
outfile <- gsub("\\\\.tif$", "-edit\\.tif", infile)
# rsdata is a complicated slot data format created by readGDAL
rsdata <- readGDAL(infile)
# change Background or missed vaule (here 0) to NoData, Deepend on
rsdata@data[rsdata@data[,1] == 0,1] <- NaN
# band Math formular, need to change deepend on caculate
lst <- rsdata@data[,1]*0.02
rsdata@data[,1] <- data.frame(band1=lst)
# Export the Bandmath result
writeGDAL(rsdata, outfile)
#### Export the bandmath result with colormap file
outpict <- gsub("-edit\\.tif", "-edit\\.tif.png" , outfile)
pict <- spplot(rsdata,
col.regions = rainbow(200, start = 2/6, end = 1))
png(filename = outpict)
print(pict)
dev.off()
####
# delete original files #unlink(infile)
#file.remove(infile)
}
}
#' @export
tir.todown <- function(list, downeddir, tolistName){
  downedFiles <- list.files(downeddir)
  todownList <- setdiff(list, downedFiles)
  Now <- format(Sys.time(), "_y%m%d_%H%M%S")
  todownListName <- paste0(todownListName, Now, ".txt")
  write.table(todownList , todownListName, quote = F, row.names = F,col.names = F)
}
#' @export
rs.untar <- function(list, path = ".", outdir = "../tif", pattern = ".tgz") {
  tarFiles_v <- list.files(path = path, pattern = pattern, all.files = T, full.
    names = T)
  sapply(tarFiles_v, function(i) {utils::untar(tarfile = i, exdir = file.path(
    outdir, tools::file_path_sans_ext(basename(i))))})
}
#' @export
tir.untarLandsat <- function(path = ".", outdir = "../L8_tifs", pattern = ".tgz")
{
  tarFiles_v <- list.files(path = path, pattern = pattern, all.files = T, full.
    names = T)
  sapply(tarFiles_v, function(i) {untar(tarfile = i, exdir = file.path(outdir,
    tools::file_path_sans_ext(basename(i))))})
}

#' Select and untar files in the list form tar dir to tif dir
#'
#'
#' @param list like LC81050292013262LGN00.tgz or LC81050292013262LGN00.tar.gz
#' @param formdir folders contain the Image usrally the download or database
#' @param todir Where the files will copy to, usually the workdir

```

```

#’ @export
rs.untar2 <- function(list, fromdir, todir){
  if (all(list %in% dir(fromdir))){
    sapply(list, function(i) {
      sceneDir <-file.path(tools::file_path_as_absolute(todir), gsub(pattern = "
        (~[~.]+)(.*)", replacement = "\\1", i))
      utils::untar(tarfile = file.path(tools::file_path_as_absolute(fromdir),i),
        exdir = sceneDir)
    })
  } else {
    stop (paste("Not all the files in", fromdir, "Use rs.todown to check it!"))
  }
}

setwd(dir.tif) ## important tips for use rLandsat8
## files <- sapply(file.path(dir.tif,list.files(dir.tif)), tools::file_path_as_
  absolute)
## l8.lst <- lapply(basename(files), ReadLandsat8)
l8.lst <- lapply(dir(dir.tif), ReadLandsat8)
bandnames <-c("aerosol", "blue", "green", "red",
  "nir", "swir1", "swir2",
  "panchromatic",
  "cirrus",
  "tirs1", "tirs2")
for (i in l8.lst) {
  sceneName <- i$metadata$landsat_scene_id
  if (!file.exists(file.path(dir.toaRad, sceneName))) {
    dir.create(file.path(dir.toaRad, sceneName), recursive = T)
  }
  for(j in bandnames){
    idx <- seq_along(bandnames)[sapply(bandnames, function(x) j %in% x)] # a number
    bandidx <- paste0("file_name_band_", idx)
    bandName <- sapply(i, "[", bandidx)[[1]]
    pngName <- paste0(bandName, ".png")
    #fileName <- paste0(tools::file_path_sans_ext(bandName), "_TOARad.tif")
    Rad.rst <- ToTOARadiance(i, j)
    writeRaster(Rad.rst, filename = file.path(dir.toaRad, sceneName,
      bandName), overwrite = T)
    png(filename = file.path(dir.toaRad, sceneName, pngName))
    par(family = "times")
    plot(Rad.rst)
    title(main = paste("Radiance at TOA of Band", idx))
    require("grid")
    grid.text(expression(paste("[", W*sr^-1*m^-2*mu*m^-1,"]")), x=unit(0.975, "npc")
      , y=unit(0.50, "npc"), rot=-90)
    dev.off()
    raster::removeTmpFiles(h = 1) ## Important tips for save hardisk
  }
}

setwd(dir.tif) ## very tips for use rLandsat8
l8.lst <- lapply(dir(dir.tif), ReadLandsat8)
bandnames <-c("aerosol", "blue", "green", "red",
  "nir", "swir1", "swir2",

```

```

"panchromatic",
"cirrus")
for (i in l8.lst) {
  sceneName <- i$metadata$landsat_scene_id
  if (!file.exists(file.path(dir.toaRef, sceneName))) {
    dir.create(file.path(dir.toaRef, sceneName), recursive = T)
  }
  for(j in bandnames){
    idx <- seq_along(bandnames)[sapply(bandnames, function(x) j %in% x)] # a number
    bandidx <- paste0("file_name_band_", idx)
    bandName <- sapply(i, "[[", bandidx)[[1]]
    # fileName <- paste0(tools::file_path_sans_ext(bandName), "_TOARef.tif")
    Ref.rst <- ToTOAReflectance(i, j)
    writeRaster(Ref.rst, filename = file.path(dir.toaRef, sceneName, bandName),
      overwrite = T)
    raster::removeTmpFiles(h = 0.5) ## Important tips for save hardisk
  }
}

setwd(dir.tif) ## very important tips for use rLandsat8
l8.lst <- lapply(dir(dir.tif), ReadLandsat8)
bandnames <-c("aerosol", "blue", "green", "red",
"nir", "swir1", "swir2",
"panchromatic",
"cirrus")
for (i in l8.lst) {
  sceneName <- i$metadata$landsat_scene_id
  if (!file.exists(file.path(dir.toaRefSun, sceneName))) {
    dir.create(file.path(dir.toaRefSun, sceneName), recursive = T)
  }
  for(j in bandnames){
    idx <- seq_along(bandnames)[sapply(bandnames, function(x) j %in% x)] # a number
    bandidx <- paste0("file_name_band_", idx)
    bandName <- sapply(i, "[[", bandidx)[[1]]
    # fileName <- paste0(tools::file_path_sans_ext(bandName), "_TOARefSun.tif")
    Ref.rst <- ToTOAReflectance(i, j, is.suncorrected = TRUE)
    writeRaster(Ref.rst, filename = file.path(dir.toaRefSun, sceneName, bandName),
      overwrite = T)
    raster::removeTmpFiles(h = 0.5) ## Important tips for save hardisk
  }
}

setwd(dir.tif) ## important tips for use rLandsat8
l8.lst <- lapply(dir(dir.tif), ReadLandsat8)
bandnames <-c("tirs1", "tirs2")
for (i in l8.lst) {
  sceneName <- i$metadata$landsat_scene_id
  if (!file.exists(file.path(dir.toaBT, sceneName))) {
    dir.create(file.path(dir.toaBT, sceneName), recursive = T)
  }
  for(j in bandnames){
    idx <- seq_along(bandnames)[sapply(bandnames, function(x) j %in% x)] + 9 # a
      number
    bandidx <- paste0("file_name_band_", idx)

```

```

    bandName <- sapply(i, "[[", bandidx)[[1]]
    #fileName <- paste0(tools::file_path_sans_ext(bandName), "_TOABT.tif")
    BT.rst <- ToAtSatelliteBrightnessTemperature(i, j)
    writeRaster(BT.rst, filename = file.path(dir.toaBT, sceneName, bandName),
               overwrite = T)
    raster::removeTmpFiles(h = 1) ## Improtant tips for save hardisk
  }
}

setwd(dir.tif) ## important tips for use rLandsat8
l8.lst <- lapply(dir(dir.tif), ReadLandsat8)
bandnames <- c("tirs1", "tirs2")
sceneList <- list.files(dir.toaTbk, full.names = TRUE)
for (i in sceneList) {
  bandList <- list.files(sceneList, full.names = TRUE)
  emiName <- paste0(basename(i), ".tif")
  pngName <- paste0(emiName, ".png")
  Tb10 <- raster::raster(bandList[1])
  Tb11 <- raster::raster(bandList[2])
  TbS <- raster::stack(Tb10, Tb11)
  a <- 1.438*10^-2
  L10 <- 10.9
  L11 <- 12.0
  TbE <- exp((a*(Tb10 - Tb11))/(Tb10*Tb11*(L10-L11)))
  Ts10 <- Tb10/(1 + (L10*Tb10/a)*log(TbE))
  writeRaster(TbE, filename = file.path(dir.toaTe, emiName), overwrite = T)
  png(file.path(dir.toaTe, pngName))
  plot(TbE)
  dev.off()
  raster::removeTmpFiles(h = 1) ## Improtant tips for save hardisk
}
}

#' Scale Raster
#' @param tif a list of tif files
if (!file.exists(dir.toaTbKlccScale)){
  dir.create(dir.toaTbKlccScale)
}
tif <- list.files(path= dir.toaTbKlcc,
pattern= ".tif$",
all.files=TRUE,
full.names=TRUE,
recursive=TRUE,
ignore.case=TRUE)
r.rst <- lapply(tif, raster)
hkdmaskb <- readRDS("~/SparkleShare/TIR/hkdmskb_grdi2d1h.Rds")
r.rstm <- lapply(r.rst, function(x) mask(x, hkdmaskb))
for (i in r.rstm) {
  outName <- paste0(names(i), ".tif")
  #projectRaster(from = i, crs = toCRS, method = "ngb",
  zscore <- raster::scale(i)
  writeRaster(zscore,
  filename = file.path(dir.toaTbKlccScale, outName),

```

```

    overwrite = T)
  raster::removeTmpFiles(h = 1) ## Important tips for save hardisk
}

#' @title Calculate LST using Arits and Carnathan 1982
#' @param Ts =  $T_b / (1 + (L * T_b / a) \ln e)$ ;  $a = hc/j$ 
#' @param h is Planck's constant ( $6.626 * 10^{-34}$  Js)
#' @param c is the velocity of light ( $2.998 * 10^8$  m/s)
#' @param j is Boltzman constant ( $1.38 * 10^{-23}$  J/K)
#' @param a is  $h * c / j$  ( $1.439 * 10^{-2}$  m/K)
#' @param e is a Raster* object with Emmissivity Value caluateded by NDVI or LULC
source("./tirSettings.R")
if (!file.exists(dir.sufTsKlcc)){
  dir.create(dir.sufTsKlcc)
}
L10 =  $10.9 * 10^{-6}$ 
L11 =  $12 * 10^{-6}$ 
h =  $6.626 * 10^{-34}$ 
c =  $2.998 * 10^8$ 
j =  $1.38 * 10^{-23}$ 
p =  $h * c / j$ 
e <- raster::raster("~/Share500sda/Landsat8/at9_Database/LULC/hkdEmissivity.tif")
tif10 <- list.files(path= dir.toaTbKlcc,
pattern= "B10.tif$",
all.files=TRUE,
full.names=TRUE,
recursive=TRUE,
ignore.case=TRUE)
r10.rst <- lapply(tif10, raster)
hkdmaskb <- readRDS("~/SparkleShare/TIR/hkdmaskb_grdi2d1h.Rds")
r10.msk <- lapply(r10.rst, function(x) mask(x, hkdmaskb))
for (i in r10.msk) {
  outName <- paste0(names(i), ".tif")
  #projectRaster(from = i, crs = toCRS, method = "ngb",
  Tsk <-  $i / (1 + (L10 * i / p) * \log(e))$ 
  writeRaster(Tsk,
  filename = file.path(dir.sufTsKlcc, outName),
  overwrite = T)
  raster::removeTmpFiles(h = 1) ## Important tips for save hardisk
}
tif11 <- list.files(path= dir.toaTbKlcc,
pattern= "B11.tif$",
all.files=TRUE,
full.names=TRUE,
recursive=TRUE,
ignore.case=TRUE)
r11.rst <- lapply(tif11, raster)
hkdmaskb <- readRDS("~/SparkleShare/TIR/hkdmaskb_grdi2d1h.Rds")
r11.msk <- lapply(r11.rst, function(x) mask(x, hkdmaskb))
for (i in r11.msk) {
  outName <- paste0(names(i), ".tif")
  #projectRaster(from = i, crs = toCRS, method = "ngb",
  Tsk <-  $i / (1 + (L11 * i / p) * \log(e))$ 

```



```

writeRaster(Tsk,
filename = file.path(dir.sufTsKlcc, outName),
overwrite = T)
raster::removeTmpFiles(h = 1) ## Important tips for save hardisk
}

### Download, reproject and subset MODIS products
source('ModisDownload.R')
load('ModisLP.RData')
modisProduct <- modisProducts()
x="MOD11A2" # Product name form modisProducts()
MRTpath='~/SparkleShare/config/MRT/bin'
h <- c(28,29)
v <- c(4,5)
dates <- c('2014.01.01','2014.12.31')
UL <- c(130000,1880000)
LR <- c(1900000,200000)
proj_type <- 'LCC'
bands_subset <- '1_0_0_0_1_0_0_0_0_0_0_0'
proj_params <- '6377397.155_6356078.963_32.8_43.2_137.5_38.0_1000000.0_1000000.0_0.0_0.0_0.0_0.0_0.0_0.0_0.0'
datum <- 'NoDatum' ## WGS is not work here, I changed ModisDownload.R from WGS84 to NODATUM
pixel_size <- 1000
### Bandsubset and Spatial Subset
ModisDownload(x=x, h = h, v=v, dates = dates, UL=UL, LR=LR, MRTpath=MRTpath, mosaic=T,proj=T, proj_type=proj_type, proj_params = proj_params, pixel_size = pixel_size)

```

.3 List of source code for selected figures

```

### ----Hokkaido study area
-----
jp1.SPDF <- getData('GADM', country='JPN', level=1, path = "~/Dropbox/2data//dataRaw/gadm2")
basemap.r <- readRDS("~/Dropbox/2data/dataProduct/hkd/hkd_google_satellite_142.5_43.5_zoom6_141018_2339.Rds")
jpVolA.spdf <- readRDS("~/Dropbox/2data/dataProduct/jpVolcanoes/jpVol1110_140812_174525.Rds")
jpVolQ.spdf <- readRDS("~/Dropbox/2data/dataProduct/jpVolcanoes/jpVol1455_140812_172148.Rds")
sap.spdf <- readRDS("~/Dropbox/2data/data/Sapporo_140817_162919.Rds")
xmin <- 139
xmax <- 146
ymin <- 41.4
ymax <- 45.8
bbox.SPDF <- ge.xy2bboxSPDF(xmin,xmax,ymin,ymax,wgs84GRS)
bh <- readRDS("~/Dropbox/2data/dataProduct/hkd/hkd_profiles_140806_164333.Rds")
bh_xy <- bh[!duplicated(bh$ID),]
bh_xy$grp <- cut(bh_xy$TD, breaks = c(0,500,1000,1500,2000,2200),
labels = c("0-500","500-1000","1000-1500","1500-2000","2000-2200"))

```

```

proj4string(jpVolQ.spdf) <- proj4string(bbox.SPDF)
volQ <- jpVolQ.spdf[bbox.SPDF,]
volA <- jpVolA.spdf[bbox.SPDF,]
hkdLand <- ge.LargestPolys(jp1.SPDF, Polygon=T)
#plot(hkdLand)
volQ2 <- jpVolQ.spdf[hkdLand,]
#volA@data
A <- c(1,7,10,12,15,18)
volAA <- volA[volA$ID %in% A,]
#volAA@data
limitsX <- c(138,147)
breaksX <- seq(limitsX[1], limitsX[2],1)
labelsX=parse(text=paste(breaksX, "~o", "*E", sep=""))
##limitsY <- c(41,47)
limitsY <- c(40,47)
breaksY <- seq(limitsY[1],limitsY[2],1)
labelsY=parse(text=paste(breaksY, "~o", "*N", sep=""))
## Layer0: Base map
ggBH <- ggmap(basemap.r, extent = "panel") +
### Layers
geom_point(data = bh_xy, aes(Lon, Lat,fill = grp, size = grp),
shape = 21, alpha = 0.9) +

scale_x_continuous(name = "Longitude",
breaks=breaksX,
labels=labelsX,
limits=limitsX,
expand = c(0.01,0.01)) +

scale_y_continuous(name = "Latitude",
breaks=breaksY,
labels=labelsY,
limits=limitsY,
expand = c(0.01,0.01)) +
theme(axis.text.y = element_text(angle = 90, hjust = 0.5, vjust = 0),
axis.title.x = element_text(vjust = 0)) +
# labs(size = "Borehole depth (m)") +
scale_size_manual("Borehole depth (m)",values=c(1,1.5,2,3,4)) +
scale_fill_brewer("Borehole depth (m)", palette="Blues")
ggVol <- ggBH +
geom_point(data = volQ@data,
aes(as.numeric(lon), as.numeric(lat),
color="blue"), shape = 17, alpha = 0.7) +
geom_point(data = volA@data,
aes(as.numeric(lon), as.numeric(lat),
color="red"), shape = 17, size = 2) +
geom_point(data = volAA@data,
aes(as.numeric(lon), as.numeric(lat)), color="white",
shape = 3, size = 2) +
scale_color_manual(name = "Volcanoes", values = c("orange","red"), labels = c("
Quaternary volcanoes","Active volcanoes")) +
geom_path(data = volQ2@data, aes(as.numeric(lon), as.numeric(lat)),size = 12,
alpha = 0.2, colour = "yellow",lineend = "round")

```

```

ggSap <- ggVol + geom_point(data = sap.spdf, aes(x = lon, y = lat), colour = "
  White") +
geom_text(data = sap.spdf, aes(x = lon, y = lat, label = name), hjust = -0.1,
  family="Times", face="italic", colour="white")

library(wrspathrow)
wrs2.SPDF <- pathrow_num(x = hkdLand, as_polys = TRUE)
#plot(wrs2.SPDF,col = "red")
#wrs2.SPDF@data
wrs2.df <- fortify(wrs2.SPDF)

ggWRS <-ggSap + geom_polygon(aes(long,lat,group=group),
  color = "grey", alpha = 0.3, fill = NA,
  linetype = 3,
  data=wrs2.df) +
geom_point(data = wrs2.SPDF@data, color = "black",
  aes(x = centroid_x, y = centroid_y, shape = MODE ))

ggWRS2 <- ggWRS + geom_text(data = wrs2.SPDF@data,
  aes(x = centroid_x, y = centroid_y),
  label = paste(wrs2.SPDF@data$PATH, wrs2.SPDF@data$ROW,"_"),
  family="Times", face = "Italic", colour="black", size = 4) +
  scale_shape_manual(name = "_WRS_2", values = 20 , labels = c("Path_and_Row"))
### Plate Boundaries

jpArc.sldf <- readRDS("~/Dropbox/2data/dataProduct/jp/jpPlateBoundary_141124_
  223221.Rds")
#plot(jpArc.sldf)
bbox2.SPDF <- ge.xy2bboxSPDF(138,147,40,47,wgs84GRS)
hkdArc.sldf <- crop(jpArc.sldf, bbox2.SPDF)
hkdArc.df <- fortify(hkdArc.sldf )
hkdArc.df <- hkdArc.df[order(hkdArc.df$lat),]
rownames(hkdArc.df) <- seq_along(hkdArc.df$lat)
# summary(hkdArc.df)
# ggWRS2 + geom_point(aes(long,lat,group=group),
# color = "red",
# linetype = 1,
# hkdArc.df) +

ggPlate <- ggWRS2 + geom_path(aes(long,lat,group=piece),
  color = "red",
  linetype = 1,
  size = 1,
  hkdArc.df) +
geom_text(aes(x = 144.5, y = 41.4, label = "Kuril_Trench"),
  hjust = -0.1, angle = 35, family="Times", colour="white",
  size = 4) +
geom_text(aes(x = 143.5, y = 40, label = "_Japan_n_Trench"),
  hjust = -0.1, angle = 90, family="Times", colour="white",
  size = 4) +
geom_text(aes(x = 139.4, y = 44, label = "Plate_Boundary"),
  hjust = -0.1, angle = 78, family="Times", colour="white",

```

```

size = 4)

jpTlines.sldf <- readRDS("~/Dropbox/2data/dataProduct/jp/jpTlines_141125_221917.
  Rds")
hkdTlines.sldf <- crop(jpTlines.sldf, bbox2.SPDF)
#plot(hkdTlines.sldf)
hkdTlines.df <- fortify(hkdTlines.sldf)
## regroup
hkdTlines.df$id2 <- 2
hkdTlines.df[hkdTlines.df$id == 1,]$id2 <- 1
hkdTlines.df[hkdTlines.df$id == 3,]$id2 <- 1
ggTlines <- ggPlate + geom_line(aes(long,lat,group=group, linetype=factor(id2)),
  color = "red",
  #linetype = 2,
  size = 1,
  hkdTlines.df) +
  scale_linetype_manual(name = "Tectonic_lines", values = c(1,3),
  labels = c("Tectonic_lines","Volcanic_front"))
ggBar <- ggTlines +
  scaleBar(lon = 139, lat = 40, distanceLon = 100,
  distanceLegend = 30, distanceLat = 15,
  dist.unit = "km", arrow.length = 60,
  arrow.distance = 680, arrow.North.size = 4,
  legend.colour = "white", arrow.North.color = "white", arrow.colour = "blue")

ggFont <- ggBar +
  #coord_equal() +
  theme_bw(base_family = "Times") +
  theme(axis.text.y = element_text(angle = 90, hjust = 0.5, vjust = 0),
  axis.title.x = element_text(vjust = 0.25))
hkd <- ggFont
### ---- Hokkaido Profile
-----
hkdBH <- readRDS("~/Dropbox/2data/dataProduct/hkd/hkd_profiles_140806_164333.Rds"
  )
hkd100 <- subset(hkdBH, (Depths >=100 ))
hkdxyz <- unique(hkdBH[,c(1:3,13)])
#plot(hkd100$Depths, hkd100$Temperature, type = "p", pch = 20)
lm_eqn = function(m) {
  l <- list(a = format(coef(m)[1], digits = 3),
  b = format(abs(coef(m)[2]), digits = 3),
  r2 = format(summary(m)$r.squared, digits = 3));
  #eq <- substitute(italic(y) == a + b %.% italic(x)*", "~~italic(r)^2~"=~r2, l)
  if (coef(m)[2] >= 0) {
    eq <- substitute(italic(T) == a + b %.% italic(D)*", "~~italic(r)^2~"=~r2,l)
  } else {
    eq <- substitute(italic(T) == a - b %.% italic(D)*", "~~italic(r)^2~"=~r2,l)
  }
  as.character(as.expression(eq))
}
r2label = lm_eqn(lm(Temperature ~ Depths, data = hkd100))
labelsY = c("100", "500", "1000", "1500", "2000", "2200")
breaksY = -as.numeric(labelsY)
labelsX = c("0", "15", "50", "90", "150", "200", "250", "300")

```

```

breaksX = as.numeric(labelsX)
hkdBH <-
#ggplot(data = hkd100, aes(x= Depths, y = Temperature)) +
ggplot(data = hkd100, aes(y = -Depths, x = Temperature)) +
geom_point(aes(color = Temperature), shape = ".") +
#geom_smooth(color = "blue") +
stat_smooth(method = "lm", color = "red") +
annotate("text", x = 200, y = -2000, label = r2label, colour="red",
size = 4, parse=TRUE, font = "Times") +
geom_vline(xintercept = 15, linetype = 2,color = "green") +
geom_vline(xintercept = 100, linetype = 3,color = "blue") +
scale_y_continuous(name = "Depth_(m)", breaks = breaksY, labels = labelsY) +
scale_x_continuous(name = expression(Temperature~(degree*C)),
breaks = breaksX, labels = labelsX) +
scale_colour_gradientn(name = expression(Temperature~(degree*C)), colours = rev(
rainbow(7)),
breaks = breaksX, labels = format(breaksX)) +
theme_bw(base_size = 12, base_family = "Times") +
theme(axis.title.x=element_text(vjust = -0.5, hjust =0.5))

# hkdBH
ggsave(plot =hkdBH, "hkdBH.pdf", width = 7, height = 5)
### ----Coefficient of deterioration-----
hkdBH <- readRDS("~/Dropbox/2data/dataProduct/hkd/hkd_profiles_140806_164333.Rds"
)
hkd100 <- subset(hkdBH, (Depths >=100 ))

models.l <- dlply(hkd100, .(ID), function(df) lm(Temperature ~ Depths, data = df)
)
# Apply coef to each model and return a data frame
coef.d <- ldply(models.l, coef)
# Print the summary of each model
modles.sum <- l_ply(models.l, summary, .print = TRUE)

wraplm <- function(m) {
  cf <- coef(m)
  t <- summary(m)$coefficients[2, c(2, 4)]
  r2 <- summary(m)$r.squared
  data.frame(intercept = cf[1], slope = cf[2], n = length(resid(m)),
slope.se = t[1], pval = t[2], R2 = r2)
}
lm.d <- ldply(models.l, wraplm)
hkd100R2df <- merge(hkd100, lm.d)
ge.df2csv(hkd100R2df)

namesY = expression(R^2)
breaksY = c(seq(0,1,0.1),0.95)
labelsY = as.character(breaksY)
colorsY = rev(rainbow(7))

namesX = "Borehole's_ID"
breaksX = seq(0,450,50)
labelsX = as.character(breaksX)
hkdR2xy <-

```

```

ggplot(data = lm.d, aes(x = ID, y= R2)) +
geom_point(shape =1) +
geom_hline(yintercept = 0.9, linetype = 2,color = "blue") +
geom_hline(yintercept = 0.95, linetype = 2,color = "blue") +
scale_x_continuous(name = namesX,
breaks = breaksX,
labels = labelsX) +
scale_y_continuous(name = namesY,
breaks = breaksY,
labels = labelsY) +
theme_bw(base_size = 12, base_family = "Times") +
theme(axis.title.x=element_text(vjust = -0.5, hjust =0.5))
# ggsave(plot =hkdR2xy, "hkdR2xy.pdf", width = 7, height = 5)

hkdR2Box <-
ggplot(lm.d, aes(x=factor(0), y =R2)) +
geom_boxplot(fill = "green",outlier.colour = "red", color ="red") +
#geom_boxplot(fill = "green", outlier.size = 0 ) +
geom_jitter(shape = ".", size = 1) +
stat_summary(fun.y="mean",geom="point",color="blue", shape = 4) +
scale_y_continuous(breaks = breaksY,
labels = labelsY,
name = namesY) +
xlab("") +
geom_hline(yintercept = 0.9, linetype = 2,color = "blue") +
geom_hline(yintercept = 0.95, linetype = 2,color = "blue") +
theme_bw(base_size = 12, base_family = "Times")
hkdR2Box1 <- hkdR2Box +
theme(axis.text.x=element_blank(),
axis.ticks.x=element_blank(),
axis.title.y=element_text(vjust = 0.2),
aspect.ratio = 7/1)
hkdR2Box2 <- hkdR2Box +
theme(axis.text.y=element_blank(),
axis.ticks.y=element_blank(),
axis.title.x=element_text(vjust = 0.2),
aspect.ratio = 1/7)+
coord_flip()
# ggsave(plot =hkdR2Box2, "hkdR2Box2.pdf", width = 7, height = 2)
hkdR2Box3 <- hkdR2Box1 +
theme(axis.title.y=element_blank(),
axis.text.y=element_blank(),
axis.ticks.y=element_blank(),
axis.title.x=element_text(0))
grid.arrange(hkdR2xy, hkdR2Box3, widths=c(0.83, 0.17),ncol =2)
### ---- Hokkaido SST, LULC and Location-----
ge.raster2df <- function(rst){
  rst <- raster(rst)
  rst.spdf <- rasterToPoints(rst, spatial=TRUE)
  rst.df <- as.data.frame(rst.spdf)
}

lulc.df <- ge.raster2df("hkdBigLULCver1402Merge.tif")
lulc.df2 <- ge.crsTransform(lulc.df, x, y, xlcc,ylcc,wgs84GRS,lccWgs84)

```

```

lulc.rst <- raster("hkdBigLULCver1402Merge.tif")
levelplot(lulc.rst)
lst.rst <- raster("hkdL8B10CenterMos.tif")
lulc.rsp <- projectRaster(lulc.rst, lst.rst, method="ngb")
# # writeRaster(lulc.rsp, "lulc100.tif")

hkdKT <- readRDS("hkd_kt3dlcc_140530_114352.Rds")
hkdKT$t <- 10^(hkdKT$KT)
hkdXyzt <- hkdKT[,c(1:3,9)]
names(hkdXyzt) <- c("x", "y", "z", "t")

lulc.df <- ge.raster2df("lulc100.tif")
lst.df <- ge.raster2df("hkdL8B10CenterMos.tif")

sst.df <- hkdXyzt[hkdXyzt$z == 1500,]
summary(sst.df)
# summary(hkdKT)
# hkdSST1500 <- hkdKT[hkdKT$Z == 1500,]
d <- as.data.frame(rbind(c(41.91, 140.87),
c(42.23, 139.94),
c(42.816, 141.299),
c(43.485, 144.159)))
names(d) <- c("lat", "lon")
dlcc <- ge.crsTransform(d, lon, lat, xlcc, ylcc, wgs84GRS, lccWgs84)
dlcc <- maxids[-4,]

rad <- 5000
dlcc$xmin <- round(dlcc$xlcc, -3) - rad
dlcc$xmax <- round(dlcc$xlcc, -3) + rad
dlcc$ymin <- round(dlcc$ylcc, -3) - rad
dlcc$ymax <- round(dlcc$ylcc, -3) + rad
dlcc$id <- 1:nrow(dlcc)
sub <- dlcc
# head(sub)
ge.subdf <- function(df, x, y, sub){
  out.l <- list() # a list of dataframe
  for (i in 1:nrow(sub)){
    xmin <- sub[i,]$xmin
    xmax <- sub[i,]$xmax
    ymin <- sub[i,]$ymin
    ymax <- sub[i,]$ymax
    x <- df$x
    y <- df$y
    out.l[[i]] <- df[x >= xmin & x <= xmax & y >= ymin & y <= ymax,]
  }
  # out.spdf <- do.call(rbind, out.l)
  # out.df <- as.data.frame(out.spdf)
  return(out.l)
}
sst.clip.l <- ge.subdf(sst.df, x, y, sub)
# #head(sst.clip.l[[1]])
lst.clip.l <- ge.subdf(lst.df, x, y, sub)
# #head(lst.clip.l[[1]])
lulc.clip.l <- ge.subdf(lulc.df, x, y, sub)

```

```

# summary(lst.clip.l[[1]])
cols = oceColorsJet(10)
lst.col.brks <- seq(-20, 20, 2)
lst.col.labs <- as.character(lst.col.brks)
lst.name <- expression(~(degree*C))

gglst <- function(df){
  ggplot(df) +
    geom_raster(aes(x,y, fill = hkdL8B10CenterMos)) +
    scale_x_continuous(labels = function(x) x/1000 -1200) +
    scale_y_continuous(labels = function(x) x/1000 -1400) +
    xlab("") +
    ylab("") +
    scale_fill_gradientn(colours = cols,
      na.value="white",
      breaks = lst.col.brks,
      labels = lst.col.labs,
      name = lst.name) +
    coord_equal() +
    theme_bw(base_size = 12, base_family = "Times") +
    theme(plot.margin = unit(c(0,-0.5,0,0), "lines"))
}

# lst1 <- gglst(lst.clip.l[[1]]) +
# annotate("text",label=paste("LST A"), x=-Inf, y=Inf, hjust=-0.4, vjust=2,
# col = "red",fontface = "bold", cex = 6)
lst.grobs <- list()
for (i in 1:4) {
  lst.grobs[[i]] <- gglst(lst.clip.l[[i]]) +
    annotate("text",label=paste("LST", LETTERS[i]), x=-Inf, y=Inf, hjust=-0.4,
      vjust=2,
      col = "red",fontface = "bold", cex = 6)
}
#lst.grobs <- list(lst1, lst2, lst3, lst4)
sst.col <- cols
sst.col.brks <- seq(0, 400, 5)
sst.col.labs <- as.character(sst.col.brks)
sst.name <- expression(~(degree*C))
ggsst <- function(df){
  geom_raster(aes(x,y, fill = t)) +
  scale_x_continuous(labels = function(x) x/1000 -1200) +
  scale_y_continuous(labels = function(x) x/1000 -1400) +
  xlab("") +
  ylab("") +
  scale_fill_gradientn(colours = sst.col,
    na.value="white",
    breaks = sst.col.brks,
    labels = sst.col.labs,
    name = sst.name) +
  coord_equal() +
  theme_bw(base_size = 12, base_family = "Times") +
  theme(plot.margin = unit(c(0,0,0,-0.5), "lines"))
}

```



```

sst.grobs <- list()
for (i in 1:4) {
  sst.grobs[[i]] <- ggsst(sst.clip.1[[i]]) +
    annotate("text",label=paste("SST", LETTERS[i]), x=-Inf, y=Inf, hjust=-0.4,
      vjust=2,
      col = "red",fontface = "bold", cex = 6)
}
lulc.col.brks <- c(1,2,3,4,5,6,8,10,11)
lulc.col.labs <- c("Water", "Urban", "Paddy", "Crop","Grass", "DeciduousForest",
"EvergreenForest", "Bare", "SnowAndIce")
lulc.cols <- c("blue", "red", "purple", "yellow", "yellowgreen", "springgreen", "
  forestgreen", "saddlebrown", "white")
lulc.name <- "LULC"
gglulc <- function(df){
  geom_raster(aes(x,y, fill = factor(lulc100))) +
  scale_x_continuous(labels = function(x) x/1000 -1200) +
  scale_y_continuous(labels = function(x) x/1000 -1400) +
  xlab("") +
  ylab("") +
  scale_fill_manual(values = lulc.cols,
na.value="white",
#breaks = lulc.col.brks,
labels = lulc.col.labs,
name = lulc.name) +
  coord_equal() +
  theme_bw(base_size = 12, base_family = "Times") +
  theme(legend.position="none") +
  theme(plot.margin = unit(c(0,-0.5,0,-0.5), "lines"))
}
lulc.grobs <- list()
for (i in 1:4) {
  lulc.grobs[[i]] <- gglulc(lulc.clip.1[[i]]) +
    annotate("text",label=paste("LULC", LETTERS[i]), x=-Inf, y=Inf, hjust=-0.4,
      vjust=2,
      col = "red",fontface = "bold", cex = 6)
}
library(gridExtra)
grid.newpage()
# grid.draw(rbind(
# cbind(ggplotGrob(grobs[[1]]), ggplotGrob(grobs[[2]]), size="last"),
# cbind(ggplotGrob(grobs[[3]]), ggplotGrob(grobs[[4]]), size="last"),
# size = "last"))
lst.col <- rbind(ggplotGrob(lst.grobs[[1]]),
ggplotGrob(lst.grobs[[2]]),
ggplotGrob(lst.grobs[[3]]),
ggplotGrob(lst.grobs[[4]]),
size = "last")
# grid.draw(lst.col)
sst.col <-rbind(ggplotGrob(sst.grobs[[1]]),
ggplotGrob(sst.grobs[[2]]),
ggplotGrob(sst.grobs[[3]]),
ggplotGrob(sst.grobs[[4]]),
size = "last")
lulc.col <-rbind(ggplotGrob(lulc.grobs[[1]]),

```

```

ggplotGrob(lulc.grobs[[2]]),
ggplotGrob(lulc.grobs[[3]]),
ggplotGrob(lulc.grobs[[4]]),
size = "last")
grid.arrange(lst.col,lulc.col, sst.col ,ncol = 3)
### ----Variogram-----
hkdbhs <- readRDS("~/Dropbox//2data//dataProduct//hkd/hkdbh_141201_110703.Rds")
hkd3dgrid <- readRDS("~/Dropbox/2data//dataProduct/hkd/hkd15hgrid_141201_111200.
  Rds")
spdf <- hkdbhs
grid <- hkd3dgrid
vgmTlog <- variogram(Tlog ~ z, spdf,
boundaries = c(seq(100,1000,100), seq(2000,45000,5000)))
plot(vgmTlog)
v.eyel <- vgm(psill = 0.155, model = "Gau", range=700, nugget=0)
v.eye <- vgm(psill = 0.125, model = "Sph", range=35000, nugget=0, add.to=v.eyel)
v.eye
fitLine.df <- variogramLine(v.eye, maxdist = 45000)
summary(v.eye)
# plot.new()
# plot(vgmTlog, v.eye, col = "red", lwd = 3, cex.lab=1.2,
# xlab = 'Distance [m]', xlim = c(0,40000),
# ylab = expression("Semivariance [ (ln~~degree*C~~)"^2~" ]"), ylim = c(0, 0.3)
# )
vplot <- ggplot() +
geom_line(data = fitLine.df, aes(x = dist, y = gamma), size = 1, color = "red") +
geom_point(data = vgmTlog, aes(x = dist, y = gamma), color = "blue")
#geom_text(aes(label=np))
vhline <- vplot + geom_hline(yintercept = c(0.125, 0.28), linetype = 2, color = "
  green") +
geom_vline(xintercept = c(700, 35000), linetype = 4, color = "orange" )
limitsX <- c(0,45000)
breaksX <- seq(limitsX[1], limitsX[2], 5000)
labelsX=c(breaksX/1000)
##limitsY <- c(41,47)
limitsY <- c(0,0.3)
breaksY <- seq(limitsY[1],limitsY[2], 0.05)
labelsY=as.character(breaksY)

vbase <- vhline +
xlab("Distance_␣[km]") +
scale_x_continuous(breaks=breaksX,
labels=labelsX,
limits=limitsX) +
ylab(expression("Semivariance_␣[␣(ln~~degree*C~~)"^2~" ]")) +
scale_y_continuous(breaks=breaksY,
labels=labelsY,
limits=limitsY)

vtext <-
vbase +
geom_text(aes(x = 30000, y = 0.29), label = "sill_␣=␣0.155", angle = 0,
family = "Times") +
geom_text(aes(x = 6000, y = 0.11), label = "sill_␣=␣0.125", angle = 0,

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family = "Times") +
geom_text(aes(x = 44000, y = 0.06), label = "Gaussian_model\n(VERTICAL)", angle
= 90,
family = "Times") +
geom_text(aes(x = 44000, y = 0.21), label = "Spherical_model\n(Lateral)", angle
= 90,
family = "Times") +
geom_text(aes(x = 6000, y = 0.02), label = "Range=700m", family = "Times") +
geom_text(aes(x = 30000, y = 0.18), label = "Range=35km", family = "Times")
# sd <- sd(vgmTlog$gamma)
# vtext + geom_ribbon(data = vgmTlog, aes(x = dist, ymin=gamma -2*sd, ymax=gamma
+2*sd),alpha=1)
hkdVariogram <- vtext +
theme_bw(base_size = 12, base_family = "Times") +
theme(axis.title.x=element_text(vjust = -0.5))
hkdVariogram
ggsave(plot = hkdVariogram, "hkdVariogram.pdf", width = 7, height = 5)
### ----Japan Zone-----
library(ggmap)
#phd.getGoogleMap(lon = 137.5, lat = 35.5, zoom = 5, prefix = "jp")
volA <- readRDS("~/Dropbox/2data/dataProduct/jpVolcanoes/jpVol110_140812_174525.
Rds")
volQ <- readRDS("~/Dropbox/2data/dataProduct/jpVolcanoes/jpVol145_140812_172148.
Rds")
jpbase <- readRDS("~/Dropbox/2data/dataProduct/jp/jp_google_terrain_137.5_35.5_
zoom5_140825_1326.Rds")
jp46 <- readRDS("~/Dropbox/2data/dataProduct/jp/jp46_140825_100251.Rds")
tokyo <- readRDS("~/Dropbox/2data/tokyo_140817_174007.Rds")
jpname <- readRDS("~/Dropbox/2data/dataProduct/jpKenName/jpKenName_140616_161141.
Rds")

# names(jpname)
jna <- jpname[,c(6,21)]
#jna[order(jna$JCODE),]
jcode <- jpname[,c(1,21)]
#jp46@data <- data.frame(jp46@data, jp46@data[match(row.names(jp46), row.names(
jcode)),])
jp46@data <- data.frame(merge(jp46@data, jcode, by = "PID"))
jcoden <- as.numeric(substring(jp46@data$JCODE,4))
jp46@data$Zone[jcoden <=1] <- 1 #HKD
jp46@data$Zone[jcoden >=2 & jcoden <=7 ] <- 2 #NEH
jp46@data$Zone[jcoden >=8 & jcoden <=23] <- 3 #CEH
jp46@data$Zone[jcoden >=24 & jcoden <=35] <- 4 #SWH
jp46@data$Zone[jcoden >=36 & jcoden <=39] <- 5 #SKK
jp46@data$Zone[jcoden >=40 & jcoden <=46] <- 6 #KYS
library(ggplot2)
library(ggmap)
library(plyr)
jp46@data$id <- rownames(jp46@data)
jp46.P2p <- fortify(jp46, region='id')
jp46.join <- join(jp46.P2p, jp46@data, by = "id")
#jp46.sort<-jp46.fort[order(jp46.fort$order), ]
# ggplot(data=jp46.fort, aes(long, lat)) +
# geom_polygon(colour='black',fill=as.factor(jp46.fort$Zone)) +

```

```

# theme_bw()
# summary(jp46.fort)
### ggplot
breaksX <- seq(128,146, 2)
labelsX=parse(text=paste(breaksX, "^o", "*E", sep=""))
breaksY <- seq(30,46, 2)
labelsY=parse(text=paste(breaksY, "^o", "*N", sep=""))
#windowsFonts(Times=windowsFont("TT Times New Roman"))
jpzone <- ggmap(jpbase, extent = "panel") +
geom_polygon(data = jp46.join, aes(x=long,y=lat,group=id,fill=as.factor(Zone)),
  alpha = 0.3) +
xlab("Longitude") + ylab("Latitude") +
geom_point(data = volQ@data, aes(as.numeric(lon), as.numeric(lat),
  color="blue"), shape = 17, alpha = 0.9) +
geom_point(data = volA@data, aes(as.numeric(lon), as.numeric(lat), color="red"),
  shape = 17, size = 3) +
scale_x_continuous(limits = c(128,146),breaks=breaksX, labels=labelsX,expand = c
  (0.01,0.01)) +
scale_y_continuous(limits = c(30,46),breaks=breaksY, labels=labelsY,expand = c
  (0.01,0.01)) +
scale_fill_manual(name = "Geothermal_Systems",values = c("1" = "red","2"="yellow",
  "3"="green","4"="blue","5"="purple", "6"="orange"), label = c("1" = "Hokkaido",
  "2"="Honshu_(NE)", "3"="Honshu_(CE)", "4"="Honshu_(SW)", "5"="Shikoku", "6"="
  Kyushu")) +
scale_color_manual(name = "Volcanoes", values = c("blue","red"), labels = c("
  Quaternary_Volcanoes","Active_Volcanoes")) + theme_bw(base_family = "Times",
  base_size = 12)
jpzone1 <- jpzone + scaleBar(lon = 142, lat = 31, distanceLon = 150, distanceLat
  = 30, distanceLegend = 60, dist.unit = "km", arrow.length = 100, arrow.
  distance = 1100, arrow.North.size = 4,legend.colour = "black", arrow.North.
  color = "black", arrow.colour = "black")

```

List of MODIS products

Product	Levle	Type	Name	GSD
MCD12C1	3	G	Land Cover Type Yearly L3 Global 0.05Deg CMG - Combined	0.05
MCD12Q1	3	G	Land Cover Type Yearly L3 Global 500m - Combined	500.00
MCD12Q2	3	G	Land Cover Dynamics Yearly L3 Global 1km - Combined	1000.00
MCD15A2	4	G	MODIS/Terra+Aqua Gridded 1KM FPAR and LAI (8-day composite)	1000.00
MCD15A3	4	G	MODIS/Terra+Aqua Gridded 1KM FPAR and LAI (4-day composite)	1000.00
MCD43A1	4	G	BRDF/Albedo Model Parameters 16-Day L3 Global 500m - Combined	500.00
MCD43A2	4	G	BRDF/Albedo Quality 16-Day L3 Global 500m - Combined	500.00
MCD43A3	4	G	Albedo 16-Day L3 Global 500m - Combined	500.00
MCD43A4	4	G	Nadir BRDF-Adjusted Reflectance 16-Day L3 Global 500m - Combined	500.00
MCD43B1	3	G	BRDF/Albedo Model Parameters 16-Day L3 Global 1km - Combined	1000.00
MCD43B2	4	G	BRDF/Albedo Quality 16-Day L3 Global 1km - Combined	1000.00
MCD43B3	3	G	Albedo 16-Day L3 Global 1km - Combined	1000.00
MCD43B4	3	G	Nadir BRDF-Adjusted Reflectance 16-Day L3 Global 1km - Combined	1000.00
MCD43C1	3	G	BRDF/Albedo Parameters 16-Day L3 0.05Deg CMG - Combined	0.05

MCD43C2	4	G	BRDF/Albedo Snow-Free Quality 16-Day L3 Global 0.05Deg CMG - Combined	0.05
MCD43C3	3	G	Albedo 16-Day L3 Global 0.05Deg CMG - Combined	0.05
MCD43C4	4	G	Nadir BRDF-Adjusted Reflectance 16-Day L3 0.05Deg CMG - Combined	0.05
MCD45A1	3	G	Burned Area Monthly L3 Global 500m - Combined	500.00
MOD01	1A	S	Level 1A Radiance - Terra	250.00,500.00,1000.00,1000.00
MOD021KM	1B	S	Level 1B Calibrated Radiance 1km - Terra	1000.00
MOD02HKM	1B	S	Level 1B Calibrated Radiance 500m - Terra	500.00
MOD02QKM	1B	S	Level 1B Calibrated Radiance 250m - Terra	250.00
MOD02SSH	1B	S	Level 1B Calibrated Radiance 5km - Terra	5000.00
MOD03	1X	S	Geolocation Fields 1km - Terra	1000.00
MOD04 _{3K}	2	S	Aerosol Product 3km - Terra	3000.00
MOD04 _{L2}	2	S	Aerosol Product - Terra	1000.00
MOD05 _{L2}	2	S	Precipitable Water - Terra	1000.00,5000.00
MOD06 _{L2}	2	S	Cloud Product - Terra	1000.00
MOD07 _{L2}	2	S	Atmospheric Profile - Terra	1000.00
MOD08 _{D3}	3	G	Atmosphere Daily Global Product - Terra	1.00
MOD08 _{E3}	3	G	Atmosphere Eight-Day Global Product - Terra	1.00
MOD08 _{M3}	3	G	Atmosphere Monthly Global Product - Terra	1.00
MOD09	2	S	Level 2 5-Min Land Surface Reflectance - 250m, 500m, 1km - Terra	250.00,500.00,1000.00
MOD09A1	3	G	Surface Reflectance 8-Day L3 Global 500m - Terra	500.00
MOD09CMG	3	G	Surface Reflectance Daily L3 Global 0.05Deg CMG - Terra	0.05
MOD09GA	2G	G	MODIS/Terra Surface Reflectance Daily L2G Global 1km and 500m SIN Grid	1000.00,500.00
MOD09GHK	2G	G	Surface Reflectance Daily L2G Global 500m - Terra	500.00
MOD09GQ	2G	G	MODIS/Terra Surface Reflectance Daily L2G Global 250m SIN Grid - Terra	250.00
MOD09GQK	2G	G	Surface Reflectance Daily L2G Global 250m - Terra	250.00
MOD09GST	2G	G	Surface Reflectance Quality Daily L2G - Terra	1000.00
MOD09Q1	3	G	Surface Reflectance 8-Day L3 Global 250m - Terra	250.00

MOD10A1	3	G	Snow Cover Daily L3 Global 500m SIN Grid - Terra	500.00
MOD10A2	3	G	Snow Cover 8-Day L3 Global 500m SIN Grid - Terra	500.00
MOD10C1	3	G	Snow Cover CMG Daily L3 Global Product 0.05Deg - Terra	0.05
MOD10C2	3	G	Snow Cover 8-Day L3 Global 0.05Deg CMG - Terra	0.05
MOD10CM	3	G	Snow Cover CMG Monthly L3 Global Product 0.05Deg - Terra	0.05
MOD10 _L 2	2	S	Snow Cover 5-Min L2 Swath 500m - Terra	500.00
MOD11A1	3	G	Land Surface Temperature/Emissivity Daily L3 Global 1km - Terra	1000.00
MOD11A2	3	G	Land Surface Temperature/Emissivity 8-Day L3 Global 1km - Terra	1000.00
MOD11B1	3	G	Land Surface Temperature/Emissivity Daily L3 Global 5km - Terra	5000.00
MOD11C1	3	G	Land Surface Temperature/Emissivity Daily L3 Global 0.05Deg CMG - Terra	0.05
MOD11C2	3	G	Land Surface Temperature/Emissivity 8-Day L3 Global 0.05Deg CMG - Terra	0.05
MOD11C3	3	G	Land Surface Temperature/Emissivity Monthly L3 Global 0.05Deg CMG - Terra	0.05
MOD11 _L 2	2	S	Land Surface Temperature/Emissivity Daily 5-Min L2 Swath 1km - Terra	1000.00
MOD12C1	3	G	Land Cover Type Yearly L3 Global 0.05Deg CMG - Terra	0.05
MOD12Q1	3	G	Land Cover Type Yearly L3 Global 1km- Terra	1000.00
MOD12Q2	3	G	Land Cover Dynamics Yearly L3 Global 1km - Terra	1000.00
MOD13A1	3	G	Vegetation Indices 16-Day L3 Global 500m - Terra	500.00
MOD13A2	3	G	Vegetation Indices 16-Day L3 Global 1km - Terra	1000.00
MOD13A3	3	G	Vegetation Indices Monthly L3 Global 1km - Terra	1000.00
MOD13C1	3	G	Vegetation Indices 16-Day L3 Global 0.05Deg CMG - Terra	0.05
MOD13C2	3	G	Vegetation Indices Monthly L3 Global 0.05Deg CMG - Terra	0.05
MOD13Q1	3	G	Vegetation Indices 16-Day L3 Global 250m - Terra	250.00
MOD14	2	S	Thermal Anomalies/Fire 5-Min L2 Swath 1km - Terra	1000.00
MOD14A1	3	G	Thermal Anomalies/Fire Daily L3 Global 1km - Terra	1000.00

MOD14A2	3	G	Thermal Anomalies/Fire 8-Day L3 Global 1km - Terra	1000.00
MOD15A2	4	G	Leaf Area Index/FPAR 8-Day L4 Global 1km - Terra	1000.00
MOD16A2	4	G	Global Evapotranspiration 8-Day	1000.00
MOD16A3	4	G	Global Evapotranspiration Yearly	1000.00
MOD17A2	4	G	Gross Primary Productivity 8-Day L4 Global 1km - Terra	1000.00
MOD17A3	3	G	Gross Primary Productivity Yearly L4 Global 1km - Terra	1000.00
MOD29	2	S	Sea Ice Extent 5-Min L2 Swath 1km - Terra	1000.00
MOD29E1D	3	G	Sea Ice Extent and IST Daily L3 Global 4km EASE-Grid Day - Terra	4000.00
MOD29P1D	3	G	Sea Ice Extent Daily L3 Global 1km EASE-Grid Day - Terra	1000.00
MOD29P1N	3	G	Sea Ice Extent Daily L3 Global 1km EASE-Grid Night - Terra	1000.00
MOD35 _L 2	2	S	Cloud Mask - Terra	250.00,1000.00
MOD43A1	4	G	BRDF/Albedo Model Parameters 16-Day L3 Global 500m - Terra	500.00
MOD43A2	4	G	BRDF/Albedo Quality 16-Day L3 Global 500m - Terra	500.00
MOD43A3	4	G	Albedo 16-Day L3 Global 500m - Terra	500.00
MOD43A4	4	G	Nadir BRDF-Adjusted Reflectance 16-Day L3 Global 500m - Terra	500.00
MOD43B1	3	G	BRDF/Albedo Model Parameters 16-Day L3 Global 1km - Terra	1000.00
MOD43B2	4	G	BRDF/Albedo Quality 16-Day L3 Global 1km - Terra	1000.00
MOD43B3	3	G	Albedo 16-Day L3 Global 1km - Terra	1000.00
MOD43B4	3	G	Nadir BRDF-Adjusted Reflectance 16-Day L3 Global 1km - Terra	1000.00
MOD43C1	3	G	BRDF/Albedo Parameters 16-Day L3 0.05Deg CMG - Terra	0.05
MOD43C2	4	G	BRDF/Albedo Snow-Free Quality 16-Day L3 Global 0.05Deg CMG - Terra	0.05
MOD43C3	3	G	Albedo 16-Day L3 Global 0.05Deg CMG - Terra	0.05
MOD43C4	4	G	Nadir BRDF-Adjusted Reflectance 16-Day L3 0.05Deg CMG - Terra	0.05
MOD44A	3	G	Vegetation Cover Conversion Quarterly L3 Global 250m	250.00

MOD44B	3	G	Vegetation Continuous Fields Yearly L3 Global 500m	500.00
MOD45A1	3	G	Burned Area Monthly L3 Global 500m - Terra	500.00
MODATML2	2	S	Atmosphere Joint Product - Terra	5000.00,10000.00
MODMGGAD	2G	G	Geolocation Angles Daily L2G Global 1km Day - Terra	1000.00
MODPT1KD	2G	G	Observation Pointers Daily L2G Global 1km Day - Terra	1000.00
MODPTHKM	2G	G	Observation Pointers Daily L2G Global 500m - Terra	500.00
MODPTQKM	2G	G	Observation Pointers Daily L2G Global 250m - Terra	250.00
MYD01	1A	S	Level 1A Radiance - Aqua	250.00,500.00,1000.00,1000.00
MYD021KM	1B	S	Level 1B Calibrated Radiance 1km - Aqua	1000.00
MYD02HKM	1B	S	Level 1B Calibrated Radiance 500m - Aqua	500.00
MYD02QKM	1B	S	Level 1B Calibrated Radiance 250m - Aqua	250.00
MYD02SSH	1B	S	Level 1B Calibrated Radiance 5km - Aqua	5000.00
MYD03	1X	S	Geolocation Fields 1km - Aqua	1000.00
MYD04 ₃ K	2	S	Aerosol Product 3km - Aqua	3000.00
MYD04 _L 2	2	S	Aerosol Product - Aqua	1000.00
MYD05 _L 2	2	S	Precipitable Water - Aqua	1000.00,5000.00
MYD06 _L 2	2	S	Cloud Product - Aqua	1000.00
MYD07 _L 2	2	S	Atmospheric Profile - Aqua	1000.00
MYD08 _D 3	3	G	Atmosphere Daily Global Product - Aqua	1.00
MYD08 _E 3	3	G	Atmosphere Eight-Day Global Product - Aqua	1.00
MYD08 _M 3	3	G	Atmosphere Monthly Global Product - Aqua	1.00
MYD09	2	S	Level 2 5-Min Land Surface Reflectance - 250m, 500m, 1km - Aqua	250.00,500.00,1000.00
MYD09A1	3	G	Surface Reflectance 8-Day L3 Global 500m - Aqua	500.00
MYD09CMG	3	G	Surface Reflectance Daily L3 Global 0.05Deg CMG - Aqua	0.05
MYD09GA	2G	G	MODIS/Aqua Surface Reflectance Daily L2G Global 1km and 500m SIN Grid	1000.00,500.00
MYD09GHK	2G	G	Surface Reflectance Daily L2G Global 500m - Aqua	500.00
MYD09GQ	2G	G	MODIS/Terra Surface Reflectance Daily L2G Global 250m SIN Grid - Aqua	250.00
MYD09GQK	2G	G	Surface Reflectance Daily L2G Global 250m - Aqua	250.00
MYD09GST	2G	G	Surface Reflectance Quality Daily L2G - Aqua	1000.00

MYD09Q1	3	G	Surface Reflectance 8-Day L3 Global 250m - Aqua	250.00
MYD10A1	3	G	Snow Cover Daily L3 Global 500m SIN Grid - Aqua	500.00
MYD10A2	3	G	Snow Cover 8-Day L3 Global 500m SIN Grid - Aqua	500.00
MYD10C1	3	G	Snow Cover CMG Daily L3 Global Product 0.05Deg - Aqua	0.05
MYD10C2	3	G	Snow Cover 8-Day L3 Global 0.05Deg CMG - Aqua	0.05
MYD10CM	3	G	Snow Cover CMG Monthly L3 Global Product 0.05Deg - Aqua	0.05
MYD10 _L 2	2	S	Snow Cover 5-Min L2 Swath 500m - Aqua	500.00
MYD11A1	3	G	Land Surface Temperature/Emissivity Daily L3 Global 1km - Aqua	1000.00
MYD11A2	3	G	Land Surface Temperature/Emissivity 8-Day L3 Global 1km - Aqua	1000.00
MYD11B1	3	G	Land Surface Temperature/Emissivity Daily L3 Global 5km - Aqua	5000.00
MYD11C1	3	G	Land Surface Temperature/Emissivity Daily L3 Global 0.05Deg CMG - Aqua	0.05
MYD11C2	3	G	Land Surface Temperature/Emissivity 8-Day L3 Global 0.05Deg CMG - Aqua	0.05
MYD11C3	3	G	Land Surface Temperature/Emissivity Monthly L3 Global 0.05Deg CMG - Aqua	0.05
MYD11 _L 2	2	S	Land Surface Temperature/Emissivity Daily 5-Min L2 Swath 1km - Aqua	1000.00
MYD13A1	3	G	Vegetation Indices 16-Day L3 Global 500m - Aqua	500.00
MYD13A2	3	G	Vegetation Indices 16-Day L3 Global 1km - Aqua	1000.00
MYD13A3	3	G	Vegetation Indices Monthly L3 Global 1km - Aqua	1000.00
MYD13C1	3	G	Vegetation Indices 16-Day L3 Global 0.05Deg CMG - Aqua	0.05
MYD13C2	3	G	Vegetation Indices Monthly L3 Global 0.05Deg CMG - Aqua	0.05
MYD13Q1	3	G	Vegetation Indices 16-Day L3 Global 250m - Aqua	250.00
MYD14	2	S	Thermal Anomalies/Fire 5-Min L2 Swath 1km - Aqua	1000.00
MYD14A1	3	G	Thermal Anomalies/Fire Daily L3 Global 1km - Aqua	1000.00
MYD14A2	3	G	Thermal Anomalies/Fire 8-Day L3 Global 1km - Aqua	1000.00

MYD15A2	4	G	Leaf Area Index/FPAR 8-Day L4 Global 1km - Aqua	1000.00
MYD17A2	4	G	Gross Primary Productivity 8-Day L4 Global 1km - Aqua	1000.00
MYD17A3	3	G	Gross Primary Productivity Yearly L4 Global 1km - Aqua	1000.00
MYD29	2	S	Sea Ice Extent 5-Min L2 Swath 1km - Aqua	1000.00
MYD29E1D	3	G	Sea Ice Extent and IST Daily L3 Global 4km EASE-Grid Day - Aqua	4000.00
MYD29P1D	3	G	Sea Ice Extent Daily L3 Global 1km EASE-Grid Day - Aqua	1000.00
MYD29P1N	3	G	Sea Ice Extent Daily L3 Global 1km EASE-Grid Night - Aqua	1000.00
MYD35 _L 2	2	S	Cloud Mask - Aqua	250.00,1000.00
MYDATML2	2	S	Atmosphere Joint Product - Aqua	5000.00,10000.00
MYDMGGAD	2G	G	Geolocation Angles Daily L2G Global 1km Day - Aqua	1000.00
MYDPT1KD	2G	G	Observation Pointers Daily L2G Global 1km Day - Aqua	1000.00
MYDPTHKM	2G	G	Observation Pointers Daily L2G Global 500m - Aqua	500.00
MYDPTQKM	2G	G	Observation Pointers Daily L2G Global 250m - Aqua	250.00

Table 1 List of MODIS products

Notations

A	Area (m^2)
a	semi-major axis
b	semi-minor axis
C	constant
c	speed of light in vacuum, $2.99792458e^8 m s^{-1}$
h	Planck's constant, $6.626068e^{-34} m^2 kg s^{-1}$
k	Boltzmann constant, $1.3806503e^{-23} m^2 kg s^{-2} K^{-1}$
$\varepsilon(\mathbf{s})$	kriging residuals
$\mu(\mathbf{s})$	kriging mean
W_i	kriging weight
$Z(\mathbf{s})$	kriging value
L	Length (m)
m	Mass (kg)
N	Number of sections
π	ratio of circumference of circle to its diameter

Q	Heat (J)
R^2	coefficient of determination
t	Time (s)
T_B	bright temperature
U	Heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
v	Velocity (m s^{-1})
x	x -coordinate
y	y -coordinate
z	z -coordinate

Abbreviations

2D	Two Dimension
3D	Three Dimension
AEA	Albers Equal-Area
AIST	The National Institute of Advanced Industrial Science and Technology
AK	Anisotropic Kriging
ALOS	Advanced Land Observing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
AVNIR-2	The Advanced Visible and Near Infrared Radiometer type 2
B.L.U.E	Best Linear Unbiased Estimator
b.s.l.	Below Sea Leave
CK	Co-Kriging
CRAN	Comprehensive R Archive Network
CRS	Coordinate Reference Systems
CTV	Comprehensive R Archive Network Task Views
DEM	Digital Elevation Model
DK	Disjunctive Kriging
DN	Digital Number

EDA	Exploratory Data Analysis
EORC	Earth Observation Research Center
EPSG	European Petroleum Survey Group Geodetic Parameter
ERTS	Earth Resources Technology Satellite
ETM+	Enhanced Thematic Mapper Plus
GCI	Geothermal Conductivity Index
GHG	Greenhouse Gases
GHP	Geothermal Heat Pumps
GIA	Geospatial Information Authority of Japan
GIS	Geographic Information System
GPP	Geothermal Power Plant
GPS	Global Positioning System
GRS	Geographic Coordinate Reference System
GSJ	Geological Survey of Japan
HSV	Hue Saturation Value
I/O	Input and Output
IDA	Initial Data Analysis
IEA	International Energy Agency
IGA	International Geothermal Association
IK	Indicator Kriging
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JAEA	Japan Atomic Energy Agency
JAXA	Japan Aerospace Exploration Agency
JGD	Japanese Geodetic Datum
JGEA	Japan Geothermal Association
JMA	Japan Meteorological Agency
JSGI	Japan Society of Geoinformatics

KED	Kriging with External Drift or trend
kW	kilowatt
LCC	Lambert conformal conic projection
LDCM	Landsat Data Continuity Mission
LK	Logistic Normal Kriging
LSE	Land Surface Emissivity
LST	Land Surface Temperature
LULC	Land-Use and Land-Cover
MODIS	MODerate resolution Imaging Spectroradiometer
MSS	Multispectral Scanner System
MW	megawatt
NASA	National Aeronautics and Space Administration
NEDO	New Energy and Industrial Technology Development Organization
NIR	Near InfraRed
NOAA	National Oceanic and Atmospheric Administration
OGC	Open Geospatial Consortium
OK	Ordinary Kriging
OLI	Operational Land Imager
PCA	Principal Component Analysis
PK	Probability Kriging
PRS	Projection Coordinate Reference System
RS	Remote Sensing
SATREPS	Science and Technology Research Partnership for Sustainable Development
SK	Simple Kriging

SRS	Spatial Reference System
SRTM	Shuttle Radar Topography Mission
SST	Subsurface Temperature
SVM	Support Vector Machine
SWIR	Short Wave InfraRed
SWIR1	Short Wave InfraRed 1
SWIR2	Short Wave InfraRed 2
TIR	Thermal Infrared Remote sensing
TIRS	Thermal InfraRed Sensor
TM	Thematic Mapper
TOA	Top of Atmosphere
UHI	Urban Heat Island
UK	Universal Kriging
USGS	United States Geological Survey
UTC	Universal Coordinated Time
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
WKB	well-known binary
WKT	well-known text
WRS	Worldwide Reference System
WRS2	Worldwide Reference System-2

Glossaries

Data curation	is the active and on-going management of data through its lifecycle of interest and usefulness to scholarship, science, and education; curation activities enable data discovery and retrieval, maintain quality, add value, and provide for re-use over time
Data integration	involves combining data from several disparate sources, which are stored using various technologies and provide a unified view of the data.
Linux	is a generic term referring to the family of Unix-like computer operating systems that use the Linux kernel

List of Associated Publications

“ Publish or perish?!”

Eugene Garfield, *The Academic Man* (1942)

- | | |
|-----------|---|
| Chapter 2 | <p>B. Tian, L. Wang, and K. Koike (2011). “Spatial statistics of surface roughness change derived from multi-scale digital elevation models”. <i>Procedia Environmental Sciences</i> 7.2005, pp. 252–257. ISSN: 18780296. DOI: 10.1016/j.proenv.2011.07.044. URL: http://linkinghub.elsevier.com/retrieve/pii/S187802961100171X (Proceeding, Poster).</p> <p>B. Tian, N. Tadakuma, H. Asaue, and K. Koike (2012a). “3D geothermal modeling by joint analyses of temperature-logging database and thermal infrared satellite images”. <i>MMIJ 2012 Spring Conference</i>, 26-28, March, 2012. Tokyo, Japan: MMIJ. URL: http://www.mmij.or.jp/ (Proceeding, Oral).</p> <p>L. Wang, B. Tian, A. Masoud, and K. Koike (2013). “Relationship between remotely sensed vegetation change and fracture zones induced by the 2008 Wenchuan earthquake, China”. <i>Journal of Earth Science</i> 24.2, pp. 282–296. ISSN: 1674-487X. DOI: 10.1007/s12583-013-0329-y. URL: http://link.springer.com/10.1007/s12583-013-0329-y.</p> |
| Chapter 3 | <p>B. Tian, N. Tadakuma, H. Asaue, and K. Koike (2012b). “Geothermal resource assessment by thermal infrared satellite imagery and 3D temperature model using well-logging data”. <i>34th International Geological Congress</i>, 5-10 August 2012. Brisbane, Australia: IUGS. URL: http://iugs.org/34igc/ (Abstract, Oral).</p> <p>B. Tian, N. Tadakuma, H. Asaue, and K. Koike (2012c). “Relationship between surface and underground temperature by joint analyses of temperature-logging database and landsat thermal infrared satellite images”. <i>First International Symposium on Land Remote Sensing May 30-June 1, 2012</i>. Chengdu, China. URL: http://www.slrss.cn/node/157 (Abstract, Oral).</p> |

- Chapter 4 B. Tian and K. Koike (2014a). "Identification of geothermal type from temperature-logging profiles with application to 3D temperature modeling". *Geological data processing*. URL: <http://www.jsgi.org/geoinforum2014.html> (Proceeding, Oral).
- Chapter 5 B. Tian and K. Koike (2014d). "Mapping spatial variability of geothermal resource in hokkaido japan by combination of thermal remote sensing and borehole data". *IEEE International Geoscience and Remote Sensing Symposium*. Quebec, Canada: IEEE, pp. 879–882. ISBN: 9781479957750. DOI: 10.1109/IGARSS.2014.6946565. URL: <http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6946565> (Proceeding, Poster).
- B. Tian, L. Wang, K. Kashiwaya, and K. Koike (2015). "Combination of well-logging temperature data and thermal remote sensing for characterizing geothermal resource: Application to Hokkaido, northern Japan". *Remote Sensing* (Accepted).
- Chapter 6 B. Tian and K. Koike (2014b). "3D crustal temperature modeling over japan for geothermal resource assessment". *16th annual conference of the International Association for Mathematical Geosciences*. New Delhi, India: IAMG. URL: <http://www.jnu.ac.in/Conference/IAMG2014/default.htm> (Proceeding).
- B. Tian and K. Koike (2014c). "Application of a well-log dataset and geostatistics to characterizing 3D temperature structure and geothermal resource assessment". *11th MMIJ young researchers conference, 12 December 2014*. Kyoto, Japan: MMIJ, p. 7. URL: <http://www.mmij.or.jp/> (Abstract, Oral).

Colophon

“Beware of bugs in the above code; I have only proved it correct, not tried it. ”

Donald Knuth, *author of T_EX*

This thesis was drafted in Emacs AucT_EX model, typeset with L^AT_EX 2_ε and T_EX version 3.14159265, and compiled on Ubuntu [Linux](#) version 14.10. It used the *PhD Thesis PSnPDF* style developed by Krishna Kumar. This style is a PhD thesis L^AT_EX template for Cambridge University Engineering Department (CUED). You can download the *PhD Thesis PSnPDF* style at <https://github.com/kks32/phd-thesis-template/>.

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- **Cross reference:** biblatex, glossaries, hyperref
- **Figures:** float, rotating
- **Tables:** array, booktab, tabu, longtable, threeparttable
- **Equations:** tocloft
- **Math and units:** amsfonts, amsmath, amssymb, siunitx
- **Miscs:** epigraph, datetime, setspace

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