MODELLING OF POTENTIAL FIELD DATA FOR SHALLOW THERMAL AND CRUSTAL STRUCTURE BENEATH PENINSULAR MALAYSIA

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by

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LIST OF SYMBOLS

k_x	Wavenumber in x direction
k_y	Wavenumber in y direction
Z_0	Depth to centroid of magnetic source
Z_b	Depth to bottom of magnetic source/Curie Point Depth
Z_t	Depth to top of magnetic source
Θ_f	Factors for field direction
Θ_m	Factors for magnetization direction
$\phi_{\Delta T}$	Power density spectra of the total field
$\propto$	Fractal index
2d	thickness of the magnetic source
A	Constant
B	Constant
C	Constant
C_m	Constant of proportionality
G	Gravitational constant
$h(x)$	Depth to the interface
HCF(k)	High cut filter
M	Magnetization
SH	Upper bound of the filter's cut-off frequency
WH	Lower bound of the filter's cut-off frequency
π	Pi
$F(\Delta g)$	Gravity anomaly Fourier Transform
dT	Temperature change
dT	Depth change
$z0$	Mean depth of the horizontal interface

β	Fractal exponent
λ	Coefficient of thermal conductivity
ρ	Density contrast across the interface

LIST OF ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
CPD	Curie Point Depth
DBMS	Depth to Bottom of Magnetic Source
EMAG2V2	Earth Magnetic Anomaly Grid 2 version 2
EMAG2V3	Earth Magnetic Anomaly Grid 2 version 3
ETOPO1	1-acr minute Earth topographic relief
GMT	Generic Mapping Tool
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GOCO06s	Gravity Observation Combination
GRACE	Gravity Recovery and Climate Experiment
ICGEM	International Centre for Global
Moho	Mohorovicic Discontinuity
NGC	National Geophysical Data
NOAA	National Oceanic and Atmospheric Administration
NW	North-west
Vp	Primary Velocity
WDMAM	World Digital Magnetic Anomaly Map
WGS-84	World Geodetic System 1984

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PEMODELAN DATA MEDAN KEUPAYAAN BAGI STRUKTUR TERMA CETEK DAN KERAK BUMI DI BAWAH SEMENANJUNG MALAYSIA

ABSTRAK

Tesis ini telah mengambil peluang-daripada kompilasi data medan keupayaan global untuk memperoleh struktur terma serantau yang pertama serta model ketebalan kerak yang paling terlerai untuk seluruh Semenanjung Malaysia dan wilayah kejiranan. Data aliran haba lubang gerek boleh memberikan maklumat paling tepat tentang struktur terma kerak, tetapi ukuran ini amat sukar diperoleh (mahal, jarang dan terhad kepada kedalaman cetek). Kedalaman ke bawah sumber magnetik (DBMS) secara tradisinya digunakan sebagai alternatif kepada data aliran haba permukaan. Dalam kajian ini, DBMS diperoleh dengan menganggap model pemagnetan fraktal dan model pemagnetan yang tidak berkorelasi rawak. Nilai DBMS menggunakan taburan fraktal sumber (~ 17 – 46 km dengan min 29 km) didapati lebih rendah daripada nilai yang dikira menggunakan kaedah rawak konvensional (29 – 67.4 km dengan nilai min 49.3 km) dan didapati cukup baik semasa mempertimbangkan kekangan tektonik dan geofizik lain. Walaupun ada perbezaan dalam nilai DBMS terbitan untuk kedua-dua kaedah, pemeriksaan visual dan plot silang menunjukkan bahawa nilai tersebut berkorelasi secara linear, dan kedua-duanya mempunyai corak dan aliran yang sama. Ketebalan kerak untuk kawasan kajian berbeza dari ~ 27.4 – 34.6 km dengan purata 30.8 km. Perbandingan antara DBMS terbitan dan ketebalan kerak menunjukkan bahawa mantel atas di bawah Sumatera barat, Singapura, lembangan Melayu, bahagian barat laut Semenanjung Malaysia, dan selatan Thailand dimagnetkan dengan ketara. Kehadiran mantel atas bermagnet menunjukkan

kestabilan kawasan ini, disebabkan oleh aliran haba yang rendah, kecerunan geoterma dan serpentinisasi.

MODELLING OF POTENTIAL FIELD DATA FOR SHALLOW THERMAL AND CRUSTAL STRUCTURE BENEATH PENINSULAR MALAYSIA

ABSTRACT

This thesis has taken advantage of the global compilation of potential field data to derive the first regional thermal structure as well as the most resolved crustal thickness model for the entire Peninsular Malaysia and neighbouring regions. Bore-hole heat flow data can provide the most precise information about the thermal structure of the crust, but these measurements are extremely difficult to obtain (expensive, sparse, and limited to shallow depths). The depth to bottom of magnetic sources (DBMS) has traditionally been used as alternative to surface heat flow data. In this study, DBMS are derived assuming random uncorrelated and fractal magnetisation models. DBMS using fractal distribution of sources (~ 17 – 46 km with a mean of 29 km) are found to be lower than the values computed using conventional random method (29 – 67.4 km with a mean value of 49.3 km) and reasonably well while considering other tectonic and geophysical constraints. Despite, the differences in the derived DBMS for the two methods, visual inspection and cross plots shows that they are linearly correlated, and they have the same pattern and trends. Crustal thickness for the study area varies from ~ 27.4 – 34.6 km with an average of 30.8 km. A comparison between the derived DBMS and crustal thickness shows that the upper mantle beneath the west Sumatra, Singapore, Malay basin, NW Peninsular Malaysia, and southern Thailand are significantly magnetised. The presence of magnetic upper mantle point to the stability of these regions attributable to low heat flow, geothermal gradient, and serpentinization.

CHAPTER 1

INTRODUCTION

1.1 Background of study

The geology of the Peninsular Malaysia has long been known as having distinguished by three north-south trending tectonic belts: the western, central, and eastern belts. Several researchers (e.g., Hutchison, 1996; Khoo & Tan, 1983; Metcalfe, 2000, 2013) have attributed the geologic contrasts among these belts to differences in stratigraphy, magmatism, and geologic evolution. The Bentong-Raub Suture Zone (BRSZ) is a major geologic feature which differentiate the western domain from the central and eastern belts (Metcalfe, 2000, 2013). The BRSZ reflects the remains of a primary ocean basin of the Paleo-Tethys that existed from the Middle Devonian to Early Triassic (Metcalfe, 2017). The western belt represents a segment of the Sibumasu terrane that emanate from the NW Australian Gondwana during the late Early Permian (Metcalfe, 2000). On the other hand, the central and eastern belts were originally part of the same tectonic block (the East Malaya block) that constitute part of the Indochina-East Malaya terrane, which split from Gondwana during the Devonian time.

Owing to its enormous potential as a source of electricity, tourism, and a possible source of drinking/mineral water (Hamzah et al., 2013), the Malaysia's hot springs have been a source of continuous interest. In particular, the presence of numerous thermal springs in western Malaysia is a strong predictor of the potential for a geothermal energy system. One well known study that is often cited in research on the thermal hot springs of Malaysia is that of Samsudin et al. (1997) which reveal 40 hot springs in the western part of the country. Subsequently, a similar study was conducted by the Minerals and Geosciences Department Malaysia (Wagner et al.,

2016) which reported 56 hot springs based on their research findings. Presently, over 60 hot springs have been mapped in western Malaysia and these thermal springs are mostly sitting on granitic intrusions along fault zones (Baioumy et al., 2015). Although, there are many reports in the literature on the exploration of Malaysia's thermal springs, however these studies are mostly restricted to geochemistry, water flow, economic viability (e.g., Baioumy et al., 2015; Chow et al., 2010; Samsudin et al., 1997) as well as mapping/delineating lithology (Anukwu et al., 2020) in the vicinity of hot springs.

So far, knowledge of the subsurface temperature/heat flow variation for the Peninsular Malaysia is lacking in the geophysical domain. Geothermal energy investigation using geochemical approach can only give an insight on the geothermal conditions of the region based on geochemical samples collected, but it cannot provide accurate information on temperature variation, depth, heat flow and geothermal gradient. Therefore, to locate and map a geothermal area, the region must have an anomalous physical property contrast different from those of the surrounding terrain. The most important physical parameters are temperature, density, seismic velocity, and rock magnetisation.

This study focused on the shallow thermal and crustal state beneath the Peninsular Malaysia (Figure 1.1) using different spectral methods. Knowledge of the thermal structure of the crust has important consequences in geosciences, since it can be used to assess the potential for geothermal, and renewable resources as well as to determine the maturity of organic matter in sedimentary basins for hydrocarbon exploration. In the exploration for geothermal resources, mapping the spatial variations in crustal temperatures and geothermal gradient is vital in characterising the geothermal energy potential (Jessop, 1998; Majorowicz & Grasby, 2010).

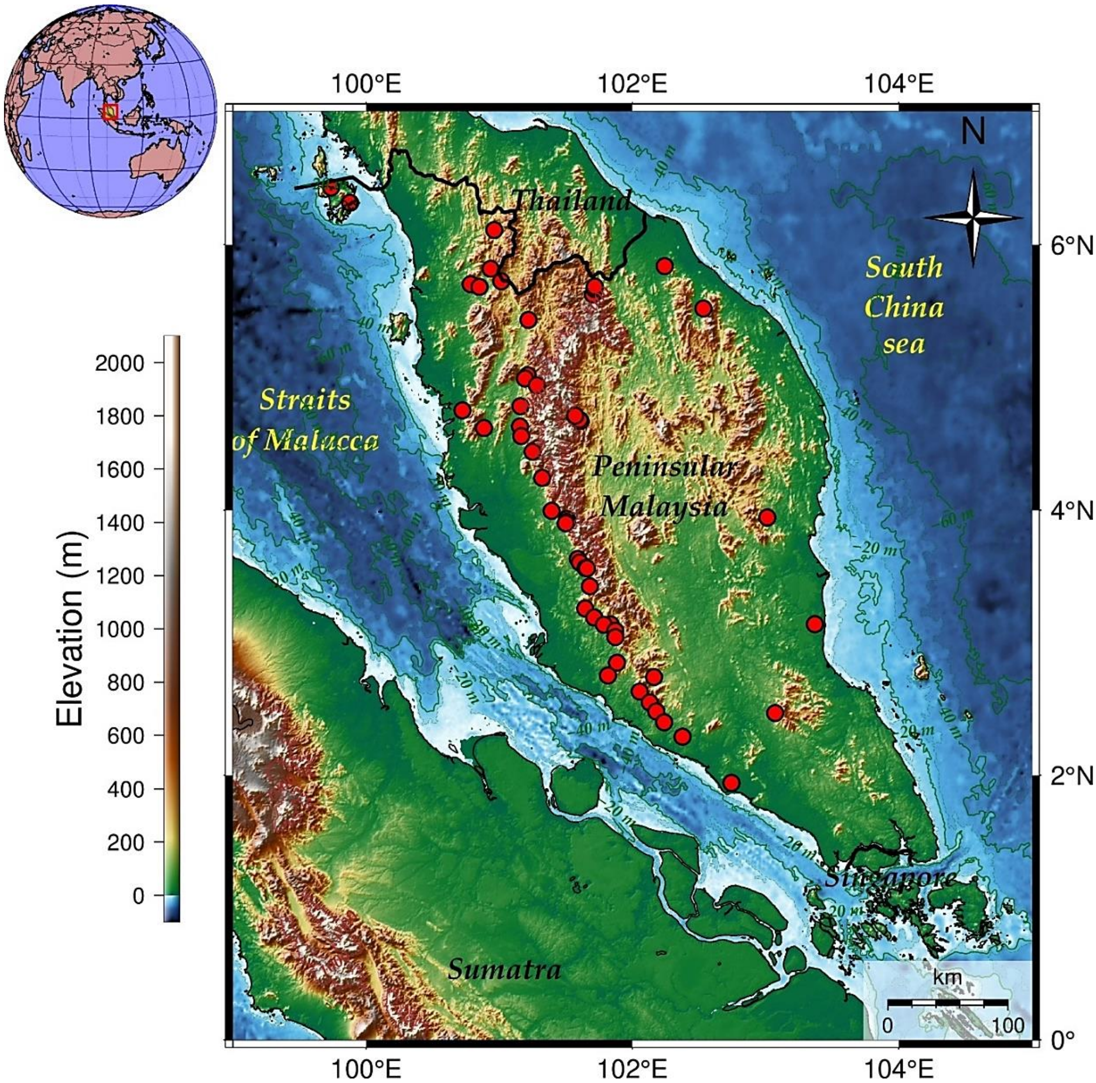

Figure 1.1 Bathymetry/Topography (ETOPO 1: Amante & Eakins, 2009) map showing locations of hot springs (red circles) in the study area.

Surface heat flow data is a major observable for inferring crustal temperature variations, however, surface heat flow measurements are very expensive and difficult to carry out since it requires drilling of a borehole onshore and drilling cores at sea (e.g., Davies, 2013; Pollack et al., 1993). Consequently, there are few heat flow data available to sufficiently constrain the regional thermal structures of the crust beneath the Peninsular Malaysia. Although, thermal structures of the crust and upper mantle can be investigated from seismic tomography, however, velocity perturbations are associated not only with temperature, but also with mineral composition (Goes et al., 2005; Priestley & Kenzie, 2006). As an alternative, the depth to bottom of magnetic sources (DBMS) has been conventionally used as a proxy for the curie point depth (CPD) and heat flow in the region. Curie point depth (e.g., Bansal et al., 2011; Okubo et al., 1985) of magnetic anomaly data provides an alternative for inferring the lithospheric temperature variation (Ross et al., 2006), since acquisition of magnetic data is relatively cheap and hence, provides uniform coverage enough for thermal studies.

The depth at which the magnetized materials lose their remanent magnetization due to the increasing crustal temperature is the curie depth. The curie point is the temperature at which rocks, and minerals lose their magnetism (Frost & Shive, 1986). Beyond this temperature, ferromagnetic minerals change to paramagnetic ones due to high temperature in the Earth's interior. In general, magnetite is regarded as the dominant magnetic mineral in the lower crust (Blakely, 1996), and it is therefore, believed that the curie temperature coincides with that of magnetite (580 ^{0}C). Although, 580 ^{0}C is the curie temperature of magnetite in its pure form, but it can reduce to 300 ^{0}C for titanium magnetite and ascend to 1100 ^{0}C for Fe-Co-Ni alloys (Blakely, 1996). Ross et al., (2006) pointed out that the use of 580 ^{0}C as the curie isotherm is a fair assumption especially for the continental crust but should be used with caution. The curie point depth is not only useful in determining the depth to the bottom of magnetic sources, but also for estimating the radiogenic heat production within the crust. Consequently, the depth to DBMS can be defined as thermal as well as magnetic boundary (Li et al., 2010). DBMS is a parameter that depends on the surface heat flow, temperature gradient, and mineral composition of the surrounding rocks (Li et al., 2010).

Calculation of magnetic layer bottom from magnetic data is often associated with uncertainties, as a result, several techniques have been developed and introduced to estimate DBMS (e.g., Bansal et al., 2011; Bhattacharyya & Leu, 1975; Maus & Dimri, 1996; Okubo et al., 1985; Tanaka et al., 1999). Early methods assume that the magnetic anomalies follow random and uncorrelated distribution of magnetic sources (Chiozzi et al., 2005; Hsieh et al., 2014; Tanaka et al., 1999). Although, this approach is interesting because of its simplicity in depth calculation, however, depth estimates are exaggerated on account of its assumption of random and uncorrelated distribution of pattern (Bansal & Dimri, 2010; Maus & Dimri, 1996). Despite its shortcomings, the method has been widely applied in many regions around the world (Chiozzi et al., 2005; Dolmaz et al., 2005; Hsieh et al., 2014; Nwankwo & Shehu, 2015; Obande et al., 2014; Tanaka et al., 1999). More recently, however, observations from boreholes suggests that the magnetisation pattern follows fractal/scaling distribution of sources (Bansal & Dimri, 2010; Bansal et al., 2011). In this study, curie point depth will be analysed using both random and fractal magnetisation methods.

It has been reported globally (Arnaiz-Rodríguez & Orihuela, 2013; Chiozzi et al., 2005; Dolmaz et al., 2005; Şalk et al., 2005; Tanaka et al., 1999) that DBMS estmates vary among different geologic terranes. In oceanic regions, several lines of evidence suggest that the observed magnetic anomalies may include contributions from both the lower crust (Dunlop & Prévot, 1982; Harrison & Carle, 1981) and the uppermost mantle (Arkani-Hamed, 1991; Wang & Li, 2015) implying that in some cases the depth to curie isotherm can reach the Moho (Mohorovicic discontinuity) or even deeper. These views were supported by the work of Li et al., (2013) in the North Atlantic which report that majority of the DBMS estimates for the North Atlantic Ocean are deeper than the Moho, suggesting that serpentinization is the source of magnetism in the upper mantle. On the other hand, in volcanic regions or areas with high heat flow, the curie isotherm is shallower than the Moho depth (Banerjee et al., 1998; Okubo et al., 1989). The curie isotherm, on the other hand, appears to be as deep as the Moho or even deeper in tectonically stable regions with low heat flow (Chiozzi et al., 2005).

Part of the aims of this study was to assess the variation in curie point depth with Moho depth throughout the study area. Investigating the relationship between the estimated curie depths and Moho depths is important because their relationship may indicate whether and how the upper-most mantle is magnetised (Wang & Li, 2015). In the Earth's crust, rock magnetization is affected by both the amount of magnetic minerals (mineral composition) and temperature. Considering the first case, at depth, the mineral composition of the crustal rocks can change, causing rocks to be deficient in magnetic minerals. Studies of xenolith samples have shown that in regions where mantle rocks are non-magnetic, DBMS estimates can be located at the Moho as against the curie isotherm (Wasilewski & Mayhew, 1992). Therefore, when DBMS coincides with the density boundary (e.g., Moho), it most likely represents a variation in mineral composition. However, when it corresponds to a different limit, it probably reflects the curie isotherm. In the latter case, the DBMS value can be used to measure the depth at which the curie temperature is reached and thus, the geothermal gradient in the studied region. Since the Moho represents the largest density contrast in the lithosphere and contributes the most, to surface gravity anomalies, Bouguer gravity anomalies have been regularly used to estimate depths to the Moho (Li et al., 2010; Li & Wang, 2016). Estimating the Moho depth can be done using several methods, one of such is the Fourier domain Parker-Oldenburg (Oldenburg, 1974; Parker, 1973) technique. The Parker-Oldenburg algorithm has been widely applied following its efficiency and ease of use in manipulating large datasets.

This thesis takes advantage of the Earth Magnetic Anomaly Grid 2 version 3 (EMAG2V3, Meyer at al., 2017), to determine the first regional model of curie point depth for the Peninsular Malaysia. The primary interest is to estimate the shallow thermal state of the crust beneath this region. Prior to this study, no previous work has investigated curie depths beneath the Peninsular Malaysia. In this study, using two different techniques (random and fractal), curie point depths were estimated in order, to better constrain the crust beneath Peninsular Malaysia continent. Consequently, these depth estimates were compared with crustal thickness estimates for the study area based on gravity data.

1.2 Statement of the Problem

The study of the crustal thermal structure has important implications in geology and tectonics due to their applications in thermal energy exploration and hydrocarbon maturity history. Thermal studies have been conducted in several locations around the world, but none has been performed on the Peninsular Malaysia, based on magnetic anomaly analysis. Even though, Peninsular Malaysia is one of the largest producers of petroleum, the thermal conditions of its intra-cratonic basins (e.g., Malay and Penyu basins) have received little or no attention. Consequently, a good knowledge of the crustal thermal conditions of the crust beneath Malaysia Peninsula will aid in a better understanding of the variations of a magnetic layer bottom.

Although, the Peninsular Malaysia continent is characterized by numerous hot springs (especially the western belt), however most of the previous studies on the thermal springs of Malaysia are focused on geochemistry, water flow, economic viability (e.g., Baioumy et al., 2015; Chow et al., 2010; Samsudin et al., 1997; Ho, 1979) as well as mapping/delineating lithology (Anukwu et al., 2020). However, this study will focus on assessing the variation in depths and heat flow throughout the area of study.

The crustal thickness beneath the Peninsular Malaysia is grossly under-studied and poorly constrained, existing literatures on this topic are mainly available at local or smaller areas. Therefore, this study has set out to investigate the crust-mantle boundary (Moho) beneath the entire Peninsular Malaysia continent using gravity data.

1.3 Research Objectives

The primary aim of this study is to investigate the thermal structure and crustal thickness beneath the Peninsular Malaysia. Different approaches exist for calculating the crustal thermal regime and thickness; however, this study aims to:

- ❖ Model the thermal structure based on random and uncorrelated magnetisation model.
- ❖ Construct the thermal structure based on 3D magnetic anomaly inversion for fractal magnetisation.
- ❖ Derive the crustal thickness model using 3D gravity inversion.

1.4 Research Novelty

This study has derived the first regional thermal model for the entire Peninsular Malaysia continent and neighbouring regions. Knowledge of the thermal conditions of the crust beneath the Peninsular Malaysia will provide insights on the crustal evolution, seismicity, subsidence/uplift, and thermal maturity of organic matter in sedimentary basins.

The study has also provided information regarding the variation of temperature gradient and heat flow for the entire crust beneath the Peninsular Malaysia. Detailed heat flow and geothermal gradient maps would help to evaluate the potential of geothermal resources, as well as those of hydrocarbons, and to better understand the geologic and tectonic evolution of this region. Further, this research could aid in assessing Malaysia's geothermal resources for future geothermal development projects and identifying the most promising areas for geothermal exploration that could be exploited for the generation of sustainable energy.

Finally, this study has presented the most resolved regional crustal thickness model for the Peninsular Malaysia. Mapping variations of crustal thickness have many important applications. Besides giving information on the crustal evolution and isostatic compensation, it is essential in investigating the relationship between the estimated curie depths and Moho depths which may indicate whether and how the upper-most mantle is magnetised. For example, when curie depths correspond to velocity or density limit (Moho), it may likely reflect a compositional change. However, when it exhibits the contrary, it is likely due to temperature change. More so, the Moho temperatures inferred from the Moho-curie depths can give clue on whether the temperature within the crust extends to upper mantle.

1.5 Thesis Structure

This dissertation is divided into five (5) different chapters: introduction, literature review, methodology, results and discussion, and conclusion.

Chapter 1 serves as a general introduction and background. It outlines the objectives, research questions, hypothesis, and significance of the research work. Chapter 2 reviews the literature related to geology, hot springs, curie point depth, and crustal thickness. It begins with the description of the regional geology of the study area. It also, review the previous work on the thermal springs of the Peninsular

Malaysia, curie point depths, and crustal thickness estimates and data gaps were identified.

The research design and methodology are presented in chapter 3. This chapter describes the data used, data collection procedure as well as the methods utilized for the study. This thesis has explored magnetic, heat flow, gravity, and topographic data sets of the Peninsular Malaysia region, mainly from the global datasets. The basic principles and derivation of different spectral methods were reviewed. There is also, a thorough discussion on windowing, fractal exponent and wavenumbers.

In chapter 4 results are presented and discussed. Results based on random and fractal methods are analysed and compared. More so, the estimated Moho depths for the study area were discussed. For each of the spectral methods used, discussions were based on the curie point depth, geothermal gradient, and heat flow estimated from the curie isotherm. In the discussion section, results were compared with previous thermal studies in other regions. Further, the variation of curie point depth with crustal thickness was assessed. Chapter 5 summarises the major findings on curie point depth, heat flow, geothermal gradient, crustal thickness estimates, and their geophysical implications. Some suggestions for possible future research are proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes literatures of previous studies related to the geology, thermal springs of Malaysia and neighbouring regions, spectral analysis of magnetic data, and crustal thickness beneath the Peninsular Malaysia. Previous studies involving the spectral analysis of magnetic data applied to different regions across the globe, were reviewed. More so, different spectral methods, assumptions, windowing, and use of other geophysical parameters were discussed. Prior studies on the estimation of crustal thickness were also in the review. Based on the discussions in the review, methodological research gaps were identified in the study area.

2.2 Regional Geologic Setting

Peninsular Malaysia represents the south-east Asian portion of the Eurasian Plate, normally referred to as the Sundaland (Hutchison, 1996; Metcalfe, 2013). The Peninsular Malaysia together with Borneo, Sumatra, Indochina, Java, and Thai Peninsular joined to form the continental block of Sundaland during the Indosinian Orogeny (Hall & Morley, 2004). It was earlier proposed that the closure of several Tethyan ocean basins between Gondwanaland and Cathayasia was responsible for the expansion of Sundaland continent in south-east Asia. Based on geology, Peninsular Malaysia is subdivided into; western, eastern and central (Figure. 2.1) rift basins and shelves of early Palaeozoic, which separates from east Gondwanaland from one continental block during the Permian-Triassic period (Metcalfe, 2000, 2013). In the western domain, Permian-Triassic granitic plutons are seen intruding Ordovician to Carboniferous rocks. Rocks of Palaeozoic age within the western domain are found in the foothills at the flanks of the Main Range granite batholith from the Thai-Malaysia boundary to Malacca (Hutchison, 1996).

The central belt extends from Kelantan in the north all the way to Johor Bahru down south. In the central domain, Palaeozoic rocks composed of mainly clastics of Permian age with traces of Carboniferous limestones exposure occurring as linear belt flanking sediments of Mesozoic age along both boundaries of the belt (Metcalfe, 2000). The Upper Palaeozoic rocks are mostly argillaceous with few calcareous and arenaceous sediments which were deposited in shallow marine environment. At the outset of the Mesozoic, most parts of Peninsular Malaysia were subaerially exposed and marine sedimentation occurred in both the NW Kodiang-Semanggol and the Gua Musang-Semantan depocenter in the central belt. While the north-western Kodiang-Semanggol depocenter formed on Sibumasu landmass, the Gua Musang-Semantan depocenter developed on the Upper Palaeozoic shelf of East Malaya (Hutchison, 1996). During the Tertiary, the Gua Musang-Semantan depocenter is characterized by widespread occurrence of tuff and its associated lava, tuffaceous siliciclastics and conglomerates and consequently, Metcalfe (2000) suggests the widespread occurrence of volcanic activities and basinal instability.

Moreover, thick sequence of turbidites were also mapped in the lower section of the Gua Musang-Semantan depocenter (Hutchison, 1977). Subsequently, after the Triassic period, new episode of regional sedimentation commences which was triggered by widespread Triassic tectonism and plutonism that gave rise to plutons in the Main Range Batholith of central and eastern belts. The occurrence of large-scale strike-slip faulting and dyke intrusions cutting across Tertiary granites in the central

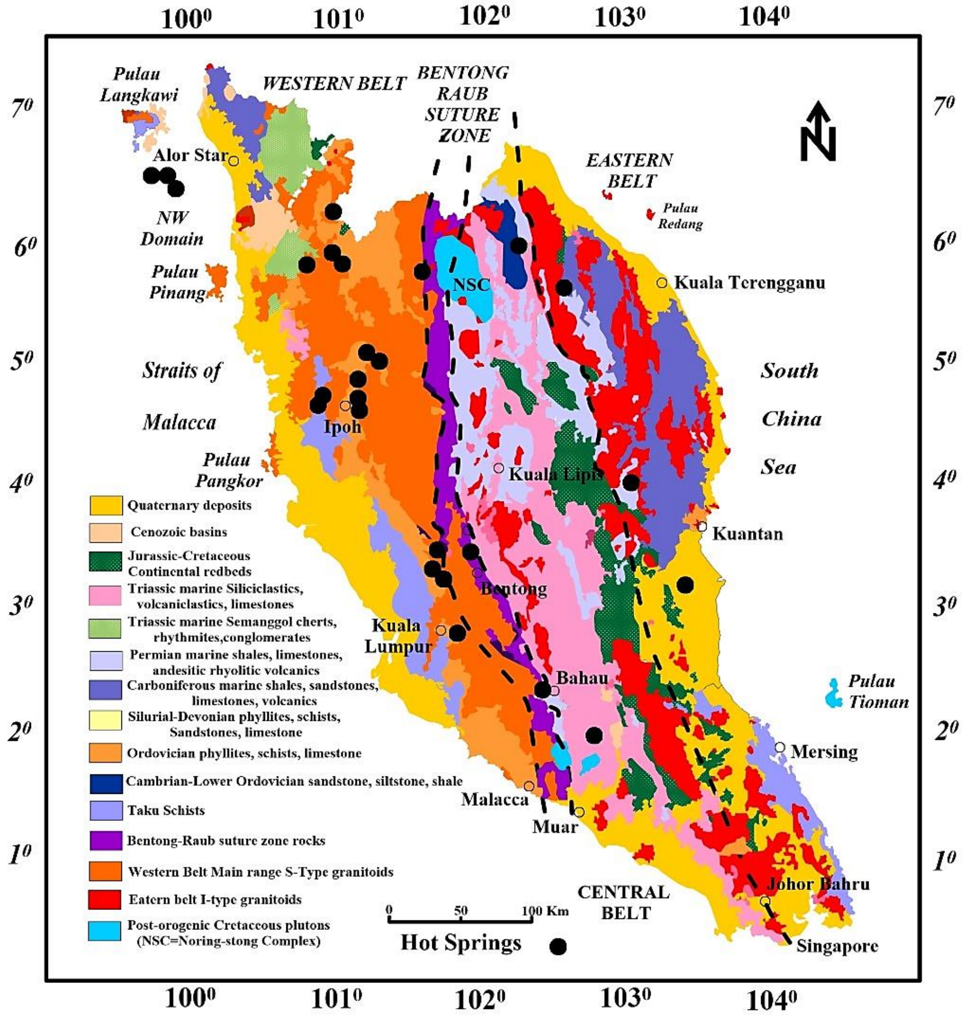

Figure 2.1 Geologic map of Peninsular Malaysia adapted from (Tate et al., 2009).

and eastern belts implies that a major extensional period have taken place during the Late to Post-Triassic period. These widespread strike-slip faulting which caused the creation of a new pull apart basins and subsequent filling of these new basins by sediments during Jurassic to Cretaceous period, marks the end of sedimentation throughout Peninsular Malaysia. The Triassic and Jurassic-Cretaceous sediments are the dominant rocks in the central belt intruded by the Triassic granite plutons (Hutchison, 1977).

The eastern belt, although at a lower elevation in relation to central belt, comprise of arc and continental basement which originated from Indochina. In the eastern belt, the prominent rocks are the Carboniferous rocks derived from the continental margin siliciclastics and carbonates that are highly deformed and have been intruded by the granitic rocks (Chakraboty & Metcalfe, 1985). In some locations, these rocks have shown phases of folding and re-folding which is suggested to be evidence of orogenic deformation associated with the closure of back arc basin. More so, in the eastern belt of Pahang and Trengganu Mississipian plants are found associated with sandstones and shales (Ohana et al., 1991).

2.2.1 Geologic Settings of Thermal Springs in West Malaysia

As was stated in the introduction section, examples of research into thermal hot springs of Malaysia includes the work of Samsudin et al. (1997) and Wagner et al. (2016). The first authors revealed 40, while the latter reported 56 thermal springs all in the western part of Malaysia. Locations of significant hot springs in the Peninsular Malaysia continent are presented in Appendix 1 (Wagner et al., 2016). Two prominent structural trends were distinguished based on their location and geologic settings. First, the East-West trend which stretched from the Tanjung Didih hot springs in Langkawi Island in the west, to the Kampung Tok Bok hot spring. This further continue to Machang, Kelantan, Kampung La hot springs and Hulu Besut of Terrangganu in the east. On the other hand, the most dominant North-South trend span from Pengkalan Hulu hot spring, Grik up north to the Gerisik thermal spring and Johor in the south (Wagner et al., 2016). This trend extends further to Sembawang and Pulau Tekong in Singapore.

These thermal springs in the western Malaysia are linked to those in Thailand as well as Myanmar. Based on geologic field mapping, Baioumy et al. (2015) shows that the north-south trending hot springs are aligned in an NNW-SSE pattern which is consistent with the major tectonic trend of the Malay Peninsula. Although, some of these thermal springs are in sedimentary terrain, however majority of them are sitting on granitic batholith along the major fault zones that separates the Peninsular into eastern and western portions (Samsudin et al., 1997). Examples of hot springs location in the study area are Ayer Hangat hot springs, Uli Slim hot springs and Lojing springs.

At Ayer Hangat hot springs, two prominent hot springs occur 200 m away from each other. These hot springs are located on alluvium sediments of Pleistocene to Recent, which consist of unconsolidated marine mud and sands forming the coastal plains . In Ulu Slim hot spring region, four hot springs were identified. Granitic rocks are the major rocks with minor metamorphic rocks south-west of the area (Baioumy et al., 2014). Two dominant structural orientation of faults in the area are N – E and NW – SE trends. The thermal springs are located on the granitic intrusions along the fault zone. The Lojing hot springs are located within the main great Range region. Lithologically, the area is divided into igneous and metamorphic terrain which are Triassic-Jurassic in age and Ordovician-Silurian respectfully (Baioumy et al., 2014).

2.2.2 Previous Work on The Thermal Springs in Peninsular Malaysia

Research into thermal springs of Malaysia has a long history. Previous research (e.g., Baioumy et al., 2015; Chow et al., 2010; Samsudin et al., 1997; Ho, 1979) focused on determining the economic viability, quality and quantity of flow of the hot springs, electricity generation, tourism, evaluating their potential as source of mineral water, as well as mapping lithology. However, there is no reported work on the geophysical study involving determination of temperature, heat flow and depths of the thermal springs.

Bott (1890), is said to have been the first to investigate the thermal hot springs in Selangor and Malacca. He described the occurrences, as well as the chemical composition of the thermal hot springs. However, for over a century, research on the thermal hot springs of Malaysia was surprisingly neglected. It was around the late 1970s, that Ho (1979), considered this topic worthy of scholarly attention. During his research, he performed a geothermometric study on hot springs in Kedah and Perak. Based on chemical geothermometric measurements, he determined the temperature of the subsurface. The research focused on the geothermal potential of hot springs for electricity generation in the northern states of Kedah and Perak.

The first serious discussions and analysis of Malaysia's thermal springs was initiated by Samsudin et al. (1997), which focused on the potential development of thermal springs for the tourism sector. The study's main aim was to find hot springs with the potential to be built commercially for tourism purposes. Although, the study initially reported 45 hot springs, but focused on the ones (40 hot springs) with high potential for tourist attraction. After considering the technological and economic viability of the various hot springs, they listed 9 hot springs with a high potential for development, 14 with a medium potential for development, and the remaining 17 with a low or no potential for development. The geological characteristics of the hot springs, locations, as well as temperature, water quality, and spring water flow rate, are among the technical indicators. Based on geology, the study found that hot springs with a high potential are located within the granitic rocks.

Like Samsudin et al. (1997), Chow et al. (2010) focused on the origin, water flow rate, and economic potential of Malaysia's hot springs for tourism. Based on their findings, surface temperature of hot springs is less than 100 ^{0}C and majority of the hot springs had flow rates ranging from 2 – 6 litres per seconds. However, one of the hot springs located at Tambun (Perak), exhibit a flow rate of 20 litres per second. In a range of geographic settings (such as along stream beds or in swampy areas), the hot springs are often found at low elevations spanning from 3 – 200 metres above sea level. The study reveals from chemical analysis of water that out of the 40 hot springs analysed, 84% of the samples had high concentration of Fluoride and Sodium that exceeded the international standards for drinking water.

Hamzah et al. (2013), carried out a water quality analysis of hot springs used for Balneotherapy around State of Selangor. Balneotherapy is a practice of immersing patients in hot mineral water bath (a treatment more common in Europe). The focus of the research was to determine the chemical concentration of Na^+, K^+, Ca^{2+}, S, SO_4^{2-} and Cl^- present in the hot springs within the study area. Majority of the thermal springs are located along the Main Range granite batholith body; however, few are found close to sedimentary rocks. The chemical analysis of the cations was carried out with aid of energy dispersive X-ray Fluorescent Spectrometry, while SO_4^{2-} and Cl^- were measured using Ion Chromatography. The results of the study indicate abnormally high concentration of salts and other minerals present in the spring water. These suggests that hot springs in Selangor are suitable for bathing and body contact, but unsuitable as portable drinking water.

Based on geochemistry, Baioumy et al., (2015) conducted a water quality analysis of 15 selected hot springs out of the 60 hot springs in western Malaysia (Appendix A) in order, to determine their origin and chemical constituents. According to geochemical evidence, most of the hot springs are Potassium-Sodium-Bicarbonate dominated, indicating uniformity in the geological formations of the study area. Consequently, the influence of local geology on the chemistry of the hot springs are also not reflected in this homogeneity. The lack of volcanic activity and proximity of the investigated hot springs to granitic intrusions, as well as their Sodium-Bicarbonate nature and low $S0_4$ content all point to a non-volcanic origin. Surface temperature of the studied hot springs varies between 41 to 99 ^{0}C with PH values ranging from 5.5 to 9. These findings along with the chemical characteristics of the hot springs under investigation point to a model that incorporates the cooling magma and thermal gradient, suggesting that the granitic intrusion from the cooling magma will raise the temperature of all rock types in the region.

In an investigation to assess the geo-tourism potential of hot springs in Hulu Langat, Selangor, Simon et al., (2019) examine hot springs based on their physico-chemical properties as well as medical benefits. Following the insitu measurements conducted, the hot springs were graded based on their PH and surface temperature. These hot springs have a PH range of 6.83 – 8.71, indicating that they are neutral to weakly alkaline. Lower temperatures (40.47 ^{0}C) were reported for Dusun Tua hot springs as against higher temperatures (74.03 ^{0}C) for IKBN hot springs. Batu 16 hot spring has high concentrations of Si, Li, Na, K, As, and Cu. Sg. Serai and Sg. Lalang hot springs have higher Fe and Ca concentrations, while Dusun Tua hot spring has the highest K concentration. It is possible that the availability of trace elements in the hot spring waters may serve as a treatment for psoriasis and eczema infections. They concluded that the presence of abundant trace elements in Batu 16 hot springs suggest that they have a potential for medical geo-tourism.

In a recent work, which set out to determine the origin and nature of the rock types in the vicinity of Ulu Slim hot springs in western Malaysia, Anukwu et al. (2020) integrated seismic refraction and multi-channel analysis of surface waves techniques in order, to enhance understanding of geology of the area. Their findings support earlier results (Baioumy et al., 2015; Samsudin et al., 1997) that the Ulu Slim hot springs are underlain by granitic intrusions.

2.2.3 Geologic Settings of Thermal Springs in Sumatra Island, Indonesia

Sumatra is located on the western edge of the Indonesian archipelago and on the Indian Ocean's north-eastern boundary. Currently, the island is made up of two major continental blocks: Cathayasia West Sumatra and northern Gondwana-origin Sibumasu. Cathayasia, which once included Indochina, South China, North Qiantang-Qamdao-Simao, West Burma, and West Sumatra, may have started moving away from Gondwana across the Paleo-Tethys Ocean during the Devonian (Metcalfe, 2013, 2011). Since the Permian, West Sumatra and West Burma have been separated from the Cathayasia and inserted at the western boundary of Sibumasu (Barber et al., 2005). Since the Miocene, the Andaman Sea has divided the two blocks.

The Medial Sumatra Tectonic Zone (MSTZ), which stretches from the Andaman Sea to southern Sumatra, marks the meeting of the West Sumatra and Sibumasu blocks (Barber et al., 2005). The intrusions under study are part of a volcanic arc sequence on the West Sumatra continental region. The plutonic rocks are near the volcanic Bukit Barisan Mountains, which run about 1,700 km from north to south across Sumatra.

Sumatra has been erupting with volcanic rocks since the pre-Triassic period. The Silungkang and Palepat Formations are Permian extrusive rock formations that can be found in central Sumatra. The Palepat Formation, which consists primarily of basic to intermediate lava, is located near Tanjung Gadang, whereas the Silungkang Formation, which is located southeast of Lake Singkarak and north of Ombilin Granite, contains of andesite and meta-andesite (Barber et al., 2005).

The majority of Tertiary volcanic rocks in Central Sumatra are located fewer than 10 km from Sumatra's west coast. Quaternary extrusive that cover a vast area in the study area can be discovered easily near mountains, lakes, and even plutons. In

Sumatra, metamorphic rocks were formed by the contact effect of intrusion and then shearing (Barber and Crow, 2009).

Two prominent hot springs province have been mapped in the Sumatra Island: The Sibayak and Silangkitang (SIL) geothermal fields. The Sibayak geothermal field is found in the province of North Sumatra, on the Indonesian island of Sumatra. Three active volcanoes, Mt. Pintau (2212 m), Mt. Sibayak (2090 m), and Mt. Pratetekan, are located within the Singkut caldera at heights ranging from 1400 to 2200 m. (1844 m). During 1989 and 1991, preliminary research were conducted over a 20x20 km region, including Mt. Sibayak. The findings of these research pointed to a region near Mt. Sibayak that may be explored further. Reservoir assessment studies, which included natural state modelling utilizing data from three exploratory wells, showed that the proved area of 4.5 km^2 has the capacity to produce steam for power generation of 39 MW for 30 years (Barber et al., 2005).

Seven more exploratory wells were drilled in the same area by 1997 to better understand the reservoir's thermal structure and establish the presence of an up-flow zone. The Silangkitang (SIL) geothermal field is located in North Sumatra Province, Indonesia, in the Tapanuli Utara District. The field is about 35 km southeast of Tarutung town. In the Sarulla contract area, Silangkitang is one of several prospects. The SIL field is located in the Barisan Mountains, which are raised physically and coated in young volcanic rocks. There are eleven active volcanoes along the mountain chain, but none of them are in the area to Sarulla. However, there are numerous volcanic eruptive centres less than 1 million years old within and next to the contract area (Barber et al., 2005).

2.2.4 Geologic Settings of Thermal Springs in Southern Thailand

Geothermal resources are abundant in many parts of Asia, providing an alternate source of energy for many of these countries while also providing advantages as a domestic energy source when contrasted to expanding fossil fuel imports. Thailand is one of the Asian countries experiencing this predicament and future scenario; nonetheless, geothermal resources exist, as evidenced by various hot spring sites with surface temperatures ranging from 35 to 100 degrees Celsius from north to south.

Chumphon, Ranong, Surat Thani, Phang Nga, Krabi, Trang, Phatthalung, Satun, and Yala are among the nine geothermal provinces in southern Thailand with thirty hot springs with surface temperatures ranging from 40 to 80 °C (Ngansom et al., 2019).

In general, there are two types of hot springs in southern Thailand: one in a general granitic setting with surface temperatures equal to or higher than 60 °C, and another in a sedimentary or metamorphic rock setting with surface temperatures less than 60 °C (Raksaskulwong, 2004). From 1983 to 2016, the Department of Mineral Resources of Thailand (DMR) and the Department of Groundwater Resources conducted preliminary geological mapping, geochemical analysis, and drilling (Raksaskulwong, 2004).

In southern Thailand, the Department of Mineral Resources (DMR) identified at least thirty hot springs spread throughout nine geothermal provinces. A number of these springs have been found along significant active strike-slip fault zones, including the Ranong Fault Zone (RFZ) and the Khlong Marui Fault Zone (KMFZ), according to their locations and geological surroundings (Raksaskulwong, 2004).

2.3 Review of Curie Point Depth Estimates

Detecting curie point depth (CPD) from magnetic data is particularly relevant in the Peninsular Malaysia, since CPD provides an independent constraint on the subsurface geothermal field. Many studies have been conducted in different parts of the world to explore the thermal structures of various regions, such as East and South-east Asia (Li & Wang, 2016; Tanaka et al., 1999), Taiwan (Hsieh et al., 2014), South China Sea (Li et al., 2010), Western United States (Bouligand et al., 2009), Nigeria (Nwankwo & Shehu, 2015; Obande et al., 2014), Turkey (Dolmaz et al., 2005), North Atlantic (Li et al., 2013), Iran (Kumar et al., 2020; Shirani et al., 2020), Scotia Sea (Martos et al., 2019), North-western South America (Quintero et al., 2019), Central India (Bansal et al., 2013), and Germany (Bansal et al., 2011).

Several methods have been introduced to provide an independent assessment of crustal and lithospheric temperature, heat flow, and geothermal gradient. Early methods assume that crustal magnetisation is completely random and uncorrelated (Bhattacharyya & Leu, 1975; Okubo et al., 1985; Tanaka et al., 1999). However, recent studies have suggested that the magnetisation behaviour is fractal in nature (Li et al., 2013; Maus et al., 1997; Salem et al., 2014). The section that follows, reviewed the different published methods applied in various regions.

2.3.1 Centroid (Random and Uncorrelated) Methods

The use of magnetic data to investigate the curie point depth was first proposed by (Spector & Grant, 1970) and later modified by Okubo et al. (1985) and Tanaka et al. (1999). This method is based on the estimation of the depth of a magnetic source from the power spectrum of magnetic anomalies after converting the data from the spatial to frequency domain. This is followed by dividing the data sets into square windows overlapping each other, application of 2-D radially averaged power spectrum, and the estimation of depth to bottom of magnetic anomaly from depth to centroid and top of magnetic sources. In a classical study, Ravat et al. (2007), compare several methods for calculating the depths to top and bottom of magnetic sources using a random and uncorrelated model, including: the centroid (Bhattacharyya & Leu, 1975; Okubo et al., 1985; Tanaka et al., 1999), spectral peak (Blakely, 1996; Connard et al., 1983), and forward modelling of the spectral peak (Ravat et al., 2007). After assessing the usage and applicability of these spectral methods by previous studies, it was recommended to use a large window size (greater than 300 km – 500 km) to ascertain that the deepest magnetic layer is captured. Additionally, processing the magnetic anomaly data for spectral analysis is discouraged, because filtering removes arbitrary regional fields which then affects the low wave number part of the spectra and thus, change the actual values of Z_b. According to these authors, despite taking all the necessary measures listed above, the results can still be incorrect, in some circumstances. As a result, the authors advocate a careful review of the results using either surface heat flow data, crustal and lithospheric thickness estimates as well as seismic velocities wherever possible.

The concept of estimating curie point depth based on magnetic data is not new, and it has been frequently used in numerous parts of the world. Bhattacharyya and Leu, (1975) mapped geothermal anomalies of Yellowstone National Park, USA using aeromagnetic data. According to the study, there is a strong association between geothermally hot regions and the thickness of magnetic layer bottom. Consequently, they conclude that proper analysis of aeromagnetic data can be useful in regional reconnaissance for possible geothermal energy resources. One of the most cited spectral study is that of (Okubo et al., 1985) in which the curie point depth for the Island of Kyushu and adjacent areas in Japan were determined using a window size of approximately 41 km. The focus of the work was to assess the geothermal resource potential of Japan using aeromagnetic data as a proxy. In this study, the spectral centroid algorithm for calculating the depth to magnetic layer was derived. Although, the algorithm requires large datasets (long wavelengths anomalies), but it has proven to be successful in estimating the depth to top and centroid of magnetic layers. It was then used to estimate the curie point depths of Japan and the results were compared with heat flow data and lithology. There are good association between curie point depth, heat flow data and regional geology. They conclude that the positive correlation between the data sets validates the use of aeromagnetic data to study geothermal areas.

Tanaka et al. (1999) demonstrated that the top bound and centroid of magnetic sources can be determined from the power spectrum of magnetic anomalies, and thus use it to estimate the basal depth of magnetic sources. This follows the implementation of power spectral density of total magnetic field by Blakely (1996). Tanaka et al., (1999), then applied this technique to study the thermal state of the crust beneath the Eastern and South-Eastern Asia. They first subdivided their study region into square windows 2^0 x 2^0 with the next window overlapping the first onse at the centre. Their results show a maximum depth to top, Z_t, of magnetic anomaly of 7 km. the centroid depths, Z_0, ranges between 7 – 26 km, while the basal depths, Z_b, varies from 9 – 46 km. Comparison of these results with geologic observations suggest that the depth to magnetic layer bottom is influenced by tectonic settings. They conclude that curie estimates are lower than 10 km in volcanic and geothermal areas, between 15 – 25 km in Island arcs and ridges, more than 20 km in Plateaus and above 30 km at Trenches.

Trifonova et al., (2009) explored the curie point depths of Bulgaria and South Romania calculated from geomagnetic measurements and compare the results with regional temperature variation and seismicity using a 150 km x 150 km windowed data. In this work, a map of the variation of magnetic layer bottom (curie point depth), for