STATUS OF THESIS

Title of thesis	Structural History of the Kinta Valley, Perak, Malaysia

I CHOONG CHEE MENG

hereby allow my thesis to be placed at the Information Resource Center (IRC) of Universiti Teknologi PETRONAS (UTP) with the following conditions:

1. The thesis becomes the property of UTP
2. The IRC of UTP may make copies of the thesis for academic purposes only.
3. This thesis is classified as

[ ] Confidential

[X] Non-confidential

If this thesis is confidential, please state the reason:

____

The contents of the thesis will remain confidential for __________ years.

Remarks on disclosure:

____

	Endorsed by
	Professor Dr Manuel Pubellier Dean Faculty of Geosciences and Petroleum Engineering Universiti Teknologi PETRONAS
Signature of Author	Signature of Supervisor
Permanent address: 117, Kg. Paya N/V, 86000 Kluang, Johor, Malaysia.	Name of Supervisor Prof. Dr. Manuel Pubellier
Date : 18 · 11 · 2013	Date : 18 · 11 · 2013

UNIVERSITI TEKNOLOGI PETRONAS

STUCTURAL HISTORY OF THE KINTA VALLEY, PERAK, MALAYSIA

by

CHOONG CHEE MENG

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

Signature:

Professor Dr Manuel Pubellier
Dean
Faculty of Geosciences and Petroleum Engineering
Universiti Teknologi PETRONAS

Main Supervisor: Prof. Dr. Manuel Pubellier

Dr Chow Weng Sum
Associate Professor
Geoscience & Petroleum Engineering Department
Universiti Teknologi PETRONAS
Bandar Seri Iskandar, 31750 Tronoh,
Perak Darul Ridzuan, MALAYSIA.

Signature:

Co-Supervisor: Assoc. Prof. Dr. Chow Weng Sum

Signature:

Head of Department: Assoc. Prof. Dr. Abdul Hadi Abd. Rahman

AP Dr Abdul Hadi B. Abd Rahman
Head, Geosciences Department
Universiti Teknologi PETRONAS

Date: 21.8.2013

STRUCTURAL HISTORY OF THE KINTA VALLEY, PERAK, MALAYSIA

by

CHOONG CHEE MENG

A Thesis

Submitted to the Postgraduate Studies Programme

as a Requirement for the Degree of

MASTER OF SCIENCE

GEOSCIENCE

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR,

PERAK

NOVEMBER 2013

DECLARATION OF THESIS

Title of thesis	Structural History of the Kinta Valley, Perak, Malaysia

I CHOONG CHEE MENG

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Witnessed by

Signature of Author

Professor Dr Manuel Pubellier
Dean
Faculty of Geosciences and Petroleum Engineering
Universiti Teknologi PETRONAS

Signature of Supervisor

Permanent address: 117, Kg. Paya N/V,
86000 Kluang, Johor, Malaysia.

Name of Supervisor
Prof. Dr. Manuel Pubellier

Date : 18-11-2013

Date : 18-11-2013

DEDICATION

This thesis is dedicated to my beloved parents, sister and brother.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincerest gratitude to my supervisor, Prof. Dr. Manuel Pubellier, who has supervised and supported me throughout my thesis with his patience and knowledge. I am indebted to Prof. Dr. Bernard J. Pierson, for accepted me as a research student in Southeast Asia Carbonate Research Laboratory (SEACARL) and for his advices at the beginning of this work. My sincere thanks also go to Assoc. Prof. Dr. Abdelaziz Abdeldayem for his guidance in the palaeo-magnetic analysis. Thank to Assoc. Prof. Dr. Chow Weng Sum and Assoc. Prof. Askury bin Abd. Kadir, for their advices and comments at my work.

I would also like to thank Universiti Teknologi PETRONAS (UTP), for providing me the opportunity to pursue my MSc degree. Thanks to Prof. Dr. Richard Major, the current head of SEACARL, for his encouragement. I also acknowledge UTP technicians, Najib, Bob, Sha, Din and Zul, for their helps in thin section making and allowed me to borrow the equipments and maps for field works.

Thanks to MyBrain15/MyMaster (a program of Malaysia Higher Education Ministry), who has covered my tuition fee at University.

My field work was made less obstacle ridden because of the presence of a few individuals. Thank Ms. Angie Ng, HR and Training Manager of Banjaran Hotsprings Retreats and Mr. Ramesh, Director of Operation of Sunway Lost World Hotel Sdn Bhd, for allowing me to conduct field works. I also thank many individuals who allow me to enter their private property when I was conducted field observation in Kinta Valley.

I also thank to my colleagues in SEACARL, Atilia Bashardin, Nor Syazwani, Nor Sara Izzati, Siti Nur Fathiyah Jamaludin, Aishah Hanafi, Nurlela, Solomon Kassa, Haylay Tsegab, Abderrahmane Dedeche, Aicha Chalabi, Omer Babiker, Hissien Adoum Alkhali and friends in UTP, Muhammad Azfar, Wani Jalil, Liyana Yunos, Maizatul Asnida, Benjamin Sautter, Juwita Hapaz, Halim, Pak Maman, Pak Eko, Phey Chee, they were sources of joy and support. Special thanks to Justin, Kian Wei and Eddie Cho, for their support and comments in my works.

Last but not least, I thank to my family for supporting me throughout all my studies at University.

ABSTRACT

Offshore Tertiary basins are the major hydrocarbon reservoirs in Malaysia. Since the production of conventional reservoirs are depleting, it is necessary to target new potential reservoirs e.g. Pre-Tertiary and/or unconventional reservoir, to fulfill the demand. Among these, fractured reservoirs in hard competent rock, have proved to be interesting in Southeast Asia (i.e. Vietnam). Kinta Valley of Perak is a suitable candidate for a potential Pre-Tertiary reservoir, since carbonaceous schist can be a good source, plus the highly fractured and karstified limestone which potentially provided enough porosity and permeability to be an economic reservoir. This study aims to identify deformations in the rocks and propose a regional structural history of the Kinta Valley. Besides, hot springs have also been studied to evaluate the fracture system that controlled the flowing of fluid. Multi-scales of analysis (regional, outcrop, hand specimen and microscopic) have been conducted in the study. Both brittle and ductile deformations have been observed. The deformations are, (i) early set of conjugate fractures or D1, which occurred in beds within contrasting rheologies, and indicates nearly E-W extension due to overloading in the basin; (ii) E-W conjugate fractures or D2, deduced an E-W compression, composed of strike-slip faults found in gently dipping limestone and conjugate fracture set in vertical limestone, (iii) thrust faults or D3 which are the continuous event of the same E-W compression, resulted in the tight folds of the limestone near the granite contact, (iv) ductile deformation, occurred in the limestone near granite contact, probably formed by limestone contacts with hot granite, partial melted has increased its mobility, and eventually resulted in simple shear, (v) N-S normal faults or D4, is an late deformation since it often crosscut other fractures, which deduce an E-W extension. Structural history of the Kinta Valley began with overloading in the late stage of the basin infilling, which results in the early set of conjugate fractures (D1). Then, the basin underwent contraction. An E-W compression occurred probably due to the termination of the

subduction, and affected limestone and other lithologies causing them to be thrusted and folded. When compression occurred, limestone was affected by hot uplifting granite and started to behave in a ductile manner. Extension in nearly E-W direction has followed after compression. It is represented by normal faults commonly found in the valley and correlated to the Tertiary grabens in Strait of Malacca. Granite and limestone have similar fracture sets, therefore we propose a dual lithologies, interconnected fracture model to describe the formation of the hot springs in the valley.

ABSTRAK

Lembangan Tertiari luar pesisir merupakan takungan hidrokarbon utama di Malaysia. Disebabkan pengeluaran takungan konvensional semakin berkurangan, ia adalah perlu menyasar takungan baru yang berpotensi seperti takungan Pra-Tertiari dan/atau tidak konvensional, untuk memenuhi permintaan. Antaranya, takungan retakan di dalam batu yang keras, telah dibuktikan menarik di Asia Tenggara iaitu Vietnam. Lembah Kinta di Perak merupakan calon yang sesuai untuk takungan Pra-Tertiari yang berpotensi, kerana syis berkarbon boleh menjadi sumber yang baik, dengan batu kapur yang berretak dan berkarstifikasi, yang berpotensi menyediakan keliangan dan kebolehtelapan yang cukup untuk menjadi takungan ekonomi. Kajian ini bertujuan untuk mengenalpasti deformasi batuan dan mencadangkan sejarah struktur serantau di Lembah Kinta. Selain itu, air panas juga telah dikaji untuk menilai sistem retakan yang mengawal aliran cecair. Analisis pelbagai skala (serantau, singkapan, spesimen tangan dan mikroskopik) telah dijalankan. Deformasi rapuh dan mulur telah diperhatikan. Deformasi adalah, (i) set retakan konjugat awal atau D1, berlaku di lapisan yang pelbagai rheologi, dan menunjukkan ekstensi pada arah hampir Timur-Barat akibat terlebih muatan di lembangan; (ii) retakan konjugat Timur-Barat atau D2, menunjukkan pemampatan pada arah Timur-Barat, terdiri daripada sesar melintang yang terbentuk dalam lapisan batu kapur yang bermiring rendah dan retakan konjugat dalam batu kapur yang bermiring tegak, (iii) sesar sungkup atau D3 adalah hasil mampatan Timur-Barat yang sama dan berterusan, mengakibatkan lipatan ketat batu kapur yang berhampiran dengan granit, (iv) deformasi mulur, berlaku dalam batu kapur berhampiran dengan granit, mungkin terbentuk akibat daripada sentuhan granit panas dan batu kapur, separa pencairan batuan telah meningkat mobiliti , dan akhirnya menyebabkan ricih mudah, (v) sesar normal Utara-Selatan atau D4, adalah deformasi lewat disebabkan ia sering memotong retakan yang lain, yang menyimpulkan ekstensi Timur-Barat. Sejarah

struktur Lembah Kinta bermula dengan muatan pada peringkat lewat dalam pengisian lembah, yang membentuk set retakan konjugat awal (D1). Kemudian, lembangan mengalami penguncupan. Pemampatan Timur-Barat berlaku mungkin disebabkan oleh penamatan subduksi, dan mempengaruhi batu kapur dan batuan lain tersesar and terlipat. Apabila mampatan berlaku, suhu batu kapur meningkat apabila ia tersentuh dengan granit, dan mula berkelakuan dengan cara yang mulur. Ekstensi dalam arah hampir Timur-Barat diikuti selepas mampatan. Ia diwakili oleh sesar normal yang biasa ditemui di lembah dan berkait rapat dengan grabens Tertiari di Selat Melaka. Granit dan batu kapur mempunyai set retakan yang sama, oleh itu kami mencadangkan model retakan dua lithologi yang saling bersambung, untuk menggambarkan pembentukan air panas di lembah.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Fractured Reservoirs

Fractured reservoir is one of the common hydrocarbon reservoir types in the world. It holds large hydrocarbon resources and represents attractive economic targets in exploratory ventures, e.g. Cuu Long Basin, Vietnam (Areshev et al., 1992). The openings of the fractures of the rocks provide the pores to accumulate oil and gas. In order to be an economic reservoir, it must also to be permeable or enough connectivity between pores (e.g. open fractures) to produce hydrocarbon. More cross-cut fracture sets such as conjugate fracture (Figure 1.1), will provide higher permeability of the rock.

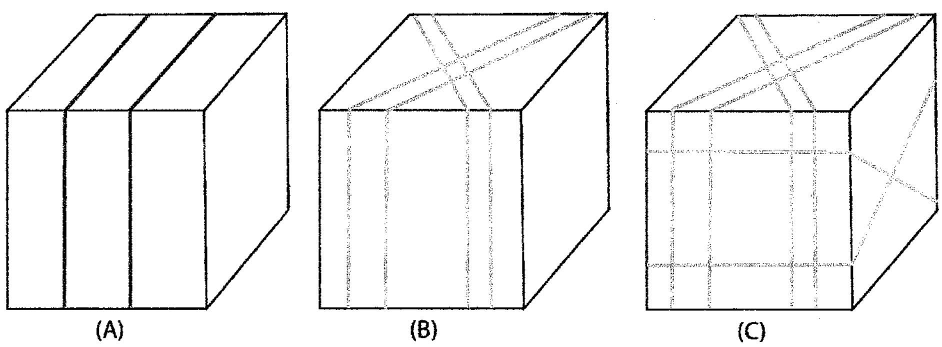


Figure 1.1 Cartoons depicting different fracture sets in brittle rocks. [A] Non-crosscut fracture set (blue lines) which are not connected to each other. Such kind of fracture set gives poor permeability. [B] Conjugate fracture set (orange lines), which connects all the fractures. Such pattern provides a better permeability. [C] Two conjugate fracture sets (orange and green lines), create higher fracture density and connectivity between fractures, which in turn generates better permeability.

It is also important that the fractures have not been filled with materials such as clay, calcite, quartz, etc, so that the porosity generated from the fractures can be maintained. Hence, the study of fractures in the brittle rocks (e.g. limestone, granite, basalt) which are competent and easily cracked, is essential to comprehend fractured hydrocarbon reservoirs.

1.2 Carbonate Reservoirs

Carbonate rocks which represent an important lithology of the Kinta Valley, can exhibit high heterogeneity even in a short distance. The varieties are induced by the diagenesis processes such as dissolution, cementation, dolomitization, compaction, etc (Barthrust, 1971; Flugel, 2004). Dissolution enhances the porosity or even permeability of a limestone, which may be makes the hydrocarbon reservoir to be economic.

Karsts are typical geomorphological features occurring in the carbonate rocks of tropical areas. Karst features are formed when the carbonate rocks are exposed to subaerial conditions, for instance dissolution by meteoric water. Cave, stalactite, stalagmite, sinkhole are some of the karst features result from the dissolution of carbonate rocks, which creates pores and connectivities between pores that lead to the formation of a good hydrocarbon reservoir. Wang and Al-Aasm (2002) indicated that the development of karsts is able to lead to the formation of hydrocarbon reservoir. Hydrocarbon reservoir developed in karsts has higher porosity and permeability compared to the average carbonate reservoir (Chilingarian et al., 1996). One of the examples could be Central Luconia carbonate province, which is the hydrocarbon reservoir in offshore East Malaysia (Figure 1.2).

Carbonate rocks are commonly competent and they deform in brittle manner in cold conditions. Thus, limestone usually exhibits high density of fractures. The open fractures increase the porosity as indicated under the aforementioned section 1.1. The Palaeozoic limestone, for example the Kinta Valley limestone, has experienced various diagenesis, and also exhibits dense fractures. And this nature may make it to be potential analogue to carbonate hydrocarbon reservoirs.

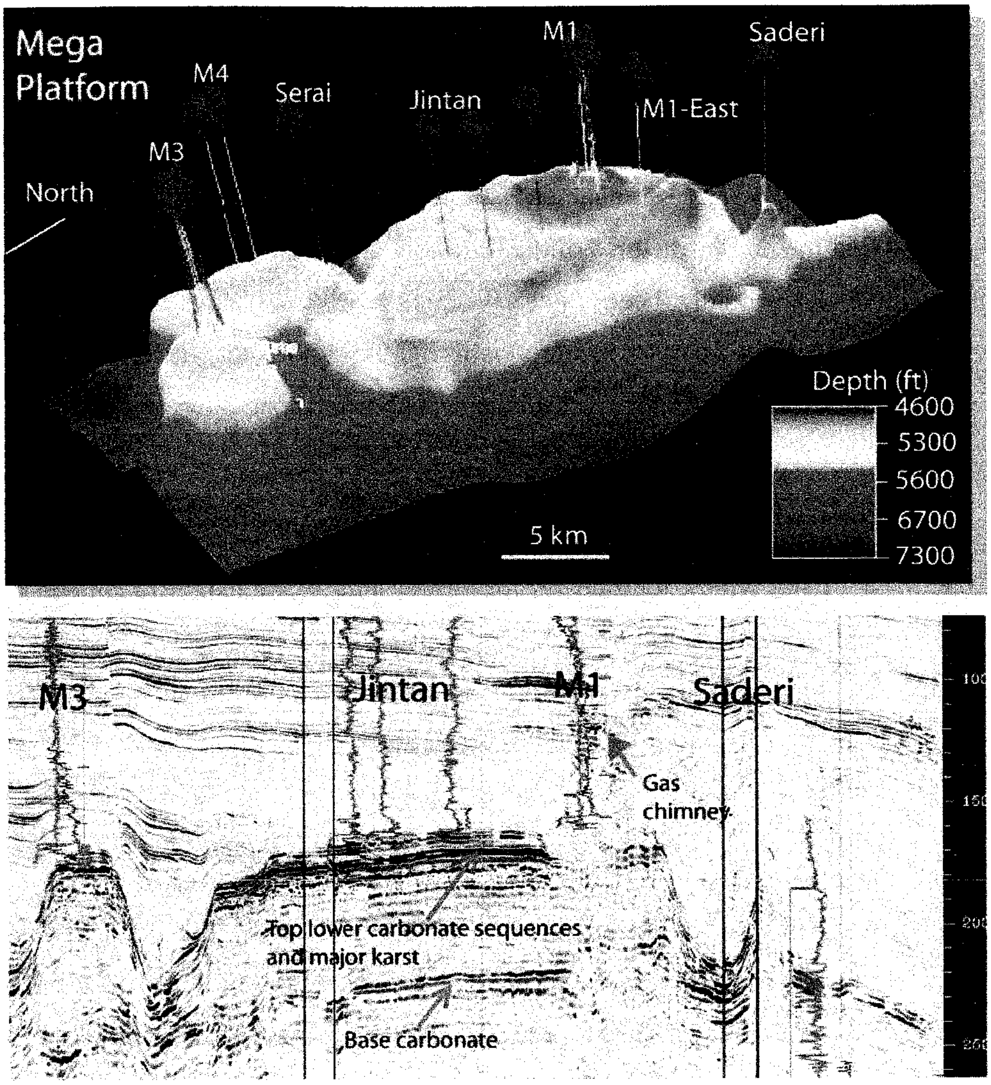


Figure 1.2 3D model (top) and cross section (bottom) of Mega Platform in Central Luconia, Sarawak. Top and base carbonates have been marked by the green arrows. The top lower carbonate sequence has been intensely karstified (red reflector). Gas Chimney is found, which may indicate the leaking of a gas reservoir. (Modified from Vahrenkamp et al., 2004)

1.3 Limestone of the Kinta Valley

Limestone of the Kinta Valley is characterized by typical tropical karsts geomorphology, where the remnant limestone hills are honeycombed with caves and pitted with dolines. Tower karsts that stand out of the alluvium deposit, which covered the valley, are also characteristic features of the Kinta Valley limestone. It is evident that the dense fractures of the limestone increased the porosity of the rock, but they have occasionally been filled by calcite. Palaeozoic limestone of the Kinta Valley, has partly been metamorphosed by the adjoining granite; as typified by crystalline limestone at the contact zone and less crystalline rock away from the contact.

The geology of Kinta Valley has been studied since the early 20th century but so far, most of the works focused on the origin and accumulation of tin ore. A few studies addressed the age and nature of the limestone, the clastic sequences and the granite (Ingham & Bradford, 1960; Lee, 2009) but our current knowledge of the structural history of the region is still mostly speculative.

The reservoir potential of Pre-Tertiary formation in Malaysia has not been given serious attention. Palaeozoic deposits found in the Peninsular Malaysia may contain all the elements of a petroleum system (Pierson et al, 2009). The Palaeozoic sequences including limestone exposed in the Kinta Valley could probably be one of the suitable materials to study its potential to be a petroleum system, however the regional complex structural history has to be thoroughly studied.

1.4 Problem Statements

Malaysia is a country rich with oil and gas reservation in offshore of the South China Sea and production is still going till now. One of the major hydrocarbon carbonate reservoirs located at the Central Luconia, Sarawak, which is a Tertiary limestone province. After a long period of production, the reservation of oil and gas has depleted. To avoid the insufficient energy supply for the daily demand, it is necessary to explore new potential Pre-Tertiary formation that may have been neglected before.

Palaeozoic deposits found in the Peninsular Malaysia may contain all the elements of a petroleum system (Pierson et al, 2009).

The limestone is hard or competent due to crystallization, and it caused the rock easily fractured. The high density of the fractures of the rocks in the Kinta Valley can be easily observed at the scale of the outcrops. The fractures are at different scales, from microscopic up to valley-sized. Tectonic activities are one of the major factors that controlled the fracture patterns of the rocks.

Could the highly fractured karsts of the Kinta Valley be considered as an example of the fractured reservoir? Tectonic events controlled the fractures patterns of the rocks (e.g. multiple fracture sets in the limestone of the Kinta Valley), which also affected the reservoir quality such as porosity and permeability. The geothermal spring located near to the limestone-granite contact could also probably gives some idea about the network and the development of the fractures. The relationship of the fractures of the limestone and the nearby granite has to be determined to reconstruct the regional structural history.

1.5 Objectives

The main objectives of this research are:

1. To study the geological structures at different scales and to determine the deformation styles in the Kinta Valley, eventually to construct a reliable regional structural history.

2. To propose the scenario of the aquifer system of the hot springs in the Kinta Valley related to the limestone and granite.

CHAPTER 2

LITERATURE REVIEW

2.1 Tectonic Evolution of Southeast Asia and Peninsular Malaysia

Peninsular Malaysia can be divided into three nearly N-S trending belts: Western Belt, Central Belt and Eastern Belt, based on their distinctive geological characteristics (Metcalfe, 2000; Lee, 2009). Main Range Granite is a mountain range which is the 'back bone' of Peninsular Malaysia. It starts from south of Malacca, Peninsular Malaysia, and extends northwards until south Thailand. It is also the eastern margin of the Western Belt. This belt is part of the Sibumasu Terrane and originated from the NW Australian Gondwana (Hutchison, 2005; Metcalfe, 2013). Bentong-Raub Suture Zone (BRSZ) marks the boundary between western and eastern part of Peninsular Malaysia. It is located at the eastern foothill of the Main Range. BRSZ is considered as the remnant of Paleo-Tethys and the boundary of the Sibumasu Terrane and an island arc, Sukhothai Arc (Metcalfe, 2013). The Central and Eastern Belts are situated south of the Sukhothai Arc which derived from Indochina Block originated from Eastern margin of the Gondwana. Tectonic evolution of the western part of Sundaland included Peninsular Malaysia during Devonian until Miocene is stated below. Pre-Cretaceous evolution in Peninsular Malaysia and Thailand is illustrated in Figure 2.1.

2.1.1 Devonian – Early Carboniferous

Tectonic evolution of Peninsular Malaysia began with continental blocks derived from Gondwana during Early Devonian. During this period, Indochina (including East Malaya), South China, North China and Tarim blocks separated from Gondwana by opening the Paleo-Tethys (Metcalfe, 1998, 2002, 2006, 2011, 2013). As the spreading continued, these blocks moved northwards.

2.1.2 Late Carboniferous – Early Permian

Sibumasu block which include the western part of Peninsular Malaysia, formed a passive margin at the Gondwana, in the southern part of the Paleo-Tethys during Late Early Permian (Metcalfe, 2013). During Carboniferous time, South China and Indochina blocks amalgamated to form a composite terrane (Metcalfe, 1998, 2013). Paleo-Tethys spreading had ceased by this time. Rifting occurred as horst and grabens on the margin of Gondwana, opening the Meso-Tethys (Metcalfe, 1998) and this time was also the initiation of the northward subduction of the Paleo-Tethys under Indochina and South China blocks (Metcalfe, 2013). The subduction led the back-arc spreading (Metcalfe, 2011) and resulted in the formation of the volcanic arc (Sukhothai Arc). This volcanic arc started to construct at the margin of the Indochina (Metcalfe, 2011, 2013).

2.1.3 Late Permian – Early Triassic

During this period, andesitic volcanism occurred on the Sukhothai Arc in East Malaya, while the arc continues its separation from the Indochina block, and subduction-related granitoids were generated in East Malaya (Metcalfe, 2000, 2013). On the Late Permian, the Shukothai back-arc basin began to contract due to the accretion between the arc and Indochina. Sibumasu began to collide with the Sukhothai Arc in the latest Permian to Early Triassic (Metcalfe, 2013).

2.1.4 Middle Triassic – Late Triassic

During Late Middle Triassic, the subduction of Palaeo-Tethys beneath Indochina block ceased (Metcalfe, 1998, 2002, 2013). The Main Range granitoids were produced by crustal thickening probably the upwelling of the hot asthenosphere following by the slab break (Metcalfe, 2000, 2013). The closure of the Sukhothai back-arc basin was completed in the Late Triassic. The subduction jumped and occurred beneath Sibumasu during Middle to Late Triassic and probably initiated the opening of the Ceno-Tethys (Metcalfe, 2013). Fold and thrusts were produced by the westward thrusts during the collision at the suture zone of the eastern part of the Sibumasu (Metcalfe, 2013). The collision may also have generated the thrusts (Kisap Thrusts) in Langkawi.

2.1.5 Jurassic

The Main Range granitoids were produced by continental crustal melting in a syn- to post-collisional setting, with latest Triassic–earliest Jurassic emplacement (Metcalfe, 2000). Peninsular Malaysia remained above sea level from Jurassic until present; blanketing sequences have been formed by the extensive continental red beds (Metcalfe, 2013).

2.1.6 Cretaceous – Early Tertiary

Peninsular Malaysia having been formed by the amalgamation of terranes during Late Palaeozoic to Early Mesozoic, remained relatively stable in tectonically afterwards. But there are still some structures that indicate deformation has been occurring in onshore and offshore of Peninsular Malaysia. A significant tectonic event during the Late Cretaceous has affected Peninsular Malaysia, such as the emplacement of isolated granitoids, folding of the red bed and remagnetization of rocks of all ages (Metcalfe, 2013). The reason of these granite emplacements still remains unclear.

2.1.7 Oligocene - Miocene

The Strait of Malacca is located at the offshore of the west coast of Peninsular Malaysia. The basement of the Malacca Strait has developed with numerous of horst and grabens. These structures were interpreted in the seismic section (Liew, 1995a). Researchers attempted to correlate these local structural patterns to the regional structure. Horst and grabens formed locally and closely, commonly with N-S striking bounding faults. Regional basement highs elongated in N-S direction and separated the group of the horst and grabens. The orientation of the horst and grabens show a rough E-W extension regime, and probably initiated by right-lateral shearing in NW-SE direction during Lower Oligocene (Liew, 1995b).

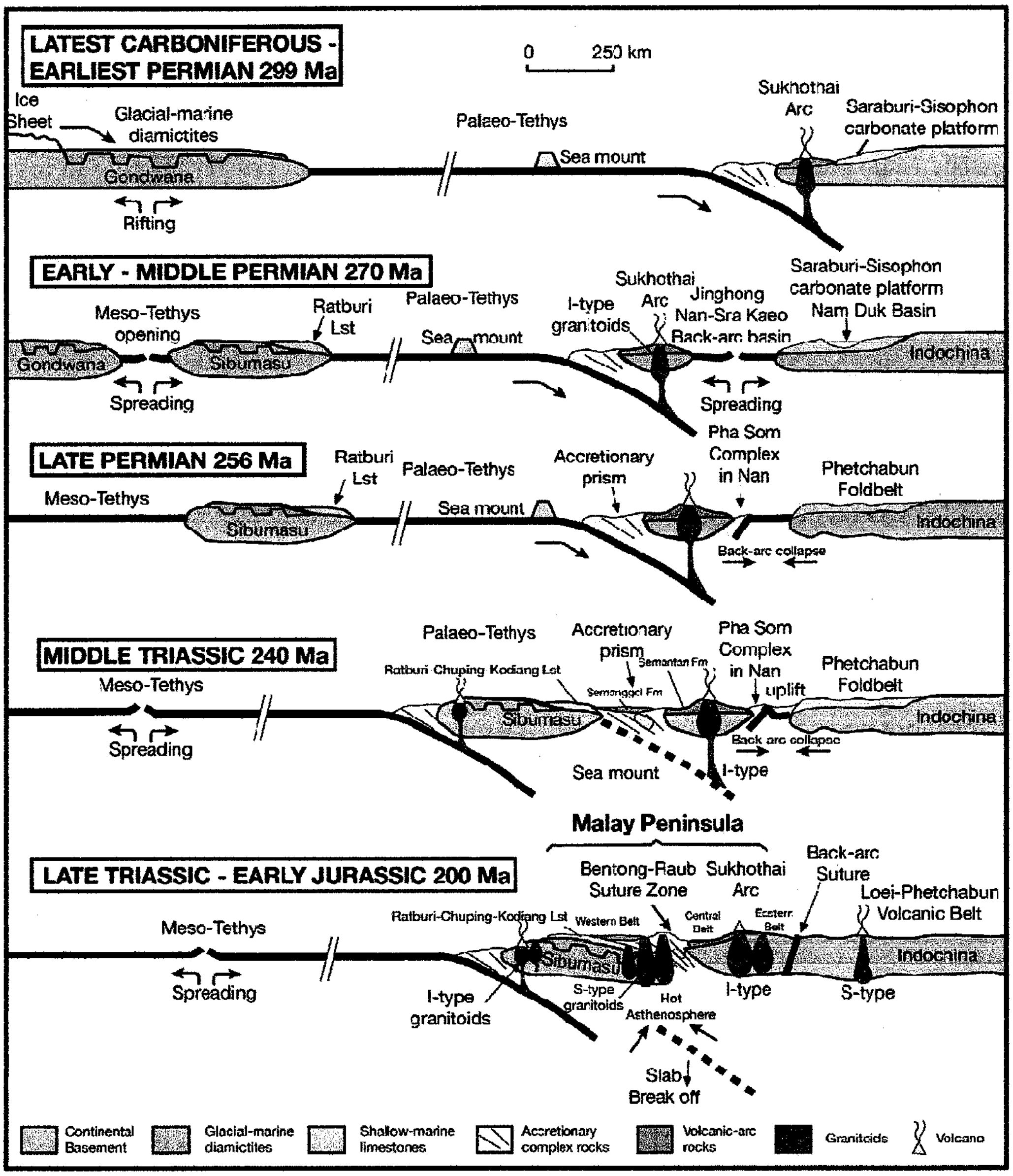


Figure 2.1 Tectonic evolution of Peninsular Malaysia and Thailand during Late Carboniferous to Early Jurassic (Metcalfe, 2013).

The Tertiary basins have also been discovered onshore Peninsular Malaysia such as Batu Arang and Layang-layang. Batu Arang basin initiated by the reactivation of the NW-SE trending faults with sinistral movement, created pull-apart half graben during Lower Eocene to Early Oligocene. Liew (1995a) considered that the onshore Peninsular Malaysia acted as the buffer zone from the opening of "Malay and Penyu Basins" and "Sumatra Basin". The stresses involved in the basin formation, were partially released through major faults and pull-apart basins in onshore Peninsular Malaysia.

Because of the lack of biostratigraphic data, the timing of the Tertiary basin formation remains unclear. Liew (1995a) proposed two hypotheses for the timing of the Tertiary basin formation, which are single event hypothesis and episodic event. In single event, the Cenozoic basins are formed during Eocene – Early Oligocene, whereas episodic event presented two periods of the basin formation, which are Eocene – Early Oligocene and Late Miocene. He preferred episodic event hypothesis because it illustrates two regional stress regimes in Tertiary which are compression initiated by sinistral movement during Eocene – Early Oligocene and reversal stress regime caused by dextral movement in Late Miocene time.

2.2 Geological setting of the Kinta Valley

Geological Survey of Federation Malaya has published a geological map of the Kinta Valley (Ingham and Bradford, 1957a, 1957b) and its cross sections are shown in Figure 2.2. It shows some information about the distribution of lithology and the geological structures in this region.

Few lithologies have been found in the Kinta Valley. Ingham & Bradford (1960) grouped the lithologies into a few geological successions of calcareous and arenaceous series, granite and alluvium. The calcareous series are composed of limestone with some clastic sedimentary and metamorphic rocks, whereas the arenaceous series are composed of quartzite intercalated with schist bands.

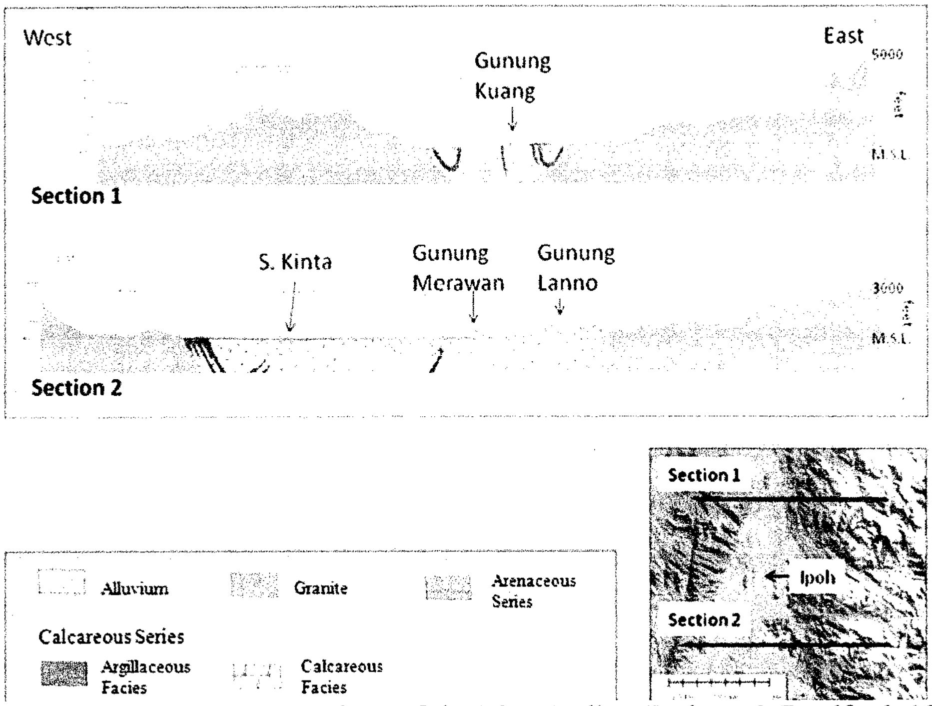


Figure 2.2 Geological cross sections of the Kinta Valley (Ingham & Bradford, 1957). The lines on the map are only approximately marked the locations of cross sections.

2.2.1 Limestone

The limestone in the Kinta Valley is named as calcareous series (Ingham & Bradford, 1960). It has been affected by contact metamorphism brought by granite intrusion, and recrystallized to form a crystallize marble (Ingham & Bradford, 1960). The area away from the granite intrusion such as West Kampar, where metamorphism effect is weak, the fossils are preserved in the rock. The age of the limestone was Carboniferous (Ingham & Bradford, 1960). Suntharalingam (1968) did the paleontological study in West Kampar and identified six rock units ranging from Middle Devonian to Middle Permian (Table 2.1), which are rich in well-preserved fossils.

Table 2.1 Rock units of the area west of Kampar, Kinta Valley. (Suntharalingam, 1968)

Rock units	Description	Thickness	Age
H.S. Lee Beds	(top not seen) Biohermal limestone	20 m	Lower Permian
	Bioclastic and fusulinid limestone	20 m	
	Impure carbonaceous brachiopod-polyzoan limestone	60 m	
	Crinoidal limestone	100m	
Kim Loong No.3 Beds	Pyritiferous black shale & argillaceous sandstone	100m	? Upper Carboniferous
Kuan On Beds	Thin-bedded grey recrystallised calcitic limestone with dolomite beds, interbedded with calcareous and carbonaceous shale	~500m	Lower Carboniferous
Thye On Beds	Massive grey recrystallised calcitic limestone	150m	Middle - ? Upper Devonian
Kim Loong No.1 Beds	Mainly pure cream-coloured dolomite (base not seen)	~ 600m	? Silurian - Lower Devonian

Thermoluminescence is a form of luminescence that emitted by heating up a mineral which previously absorbed the energy from the electromagnetic radiation. The luminescence indices will be higher in the older mineral/rock because it received radiation during a longer period. This argument will only be valid if the mineral/rock has never been heated up after formation. It is a method other than palaeontology, which is applied to differentiate the limestone of the Peninsular Malaysia (Hutchison, 1968). The work (Hutchison, 1968) shows that the thermoluminescence indices of the older limestone (Setul Formation: Ordovician-Silurian; limestone of the Kinta Valley: Devonian-Early Permian; limestone of the Kuala Lumpur: Middle-Late Palaeozoic) are lower than the younger Chuping limestone (Permian). It is emphasized that the thermoluminescence of the limestone do not reflect the stratigraphic origin but the high temperature geological events, such as intrusion.

Fontaine & Amnan (1995) interpreted that the limestone of the Kampar area is formed in a relatively quiet environment; and similarly Pierson et al. (2009) interpreted that the limestone of the Kinta Valley was deposited in a low energy environment located at the bottom of the slope near to the deep sea. The interpretation of Pierson et al. (2009) is based on the common occurrence of thinly bedded or laminated micritic limestone bands, chert layer interbedded with the limestone and slump structures that frequently present in the Kinta Valley.

The sedimentary sequences and fossils of the Kinta Valley are different from the Carboniferous – Lower Permian Singa Formation at NW Peninsular Malaysia (Fortaine & Amnan, 1995). This great difference conflicts with the general idea that West Peninsular Malaysia is formed by a single paleogeographic unit. Tjia & Zaiton (1985) suggested the hypothesis of two 'geologic domain' for West Peninsular Malaysia and NW Peninsular Malaysia, rather than single domain - Western Belt. It can probably explain the difference, which is based on their structural grounds, but the boundary is not well defined.

2.2.2 Shale, Schist and Other Meta-sedimentary Rocks

In the Kinta Valley, shale, schist and other meta-sedimentary rocks such as phyllite and quartzite are grouped as argillaceous facies within calcareous series (Ingham & Bradford, 1960). These rocks are commonly interbedded with the limestone (Savage, 1937; Ingham, 1938). Based on this evidence, they considered these lithologies are not part of the Triassic system. The ages of these rocks are at Carboniferous age (Ingham & Bradford, 1960).

Carbonaceous shale and schist can also be found in many places in Western Belt of the Peninsular Malaysia, which commonly Palaeozoic age. Since the shale/schist of the Kinta Valley has not been well dated, similar lithologies away from Kinta Valley will be taken into account, to obtain an idea about their age.

Kati beds are one of the closer rock units which occurred mostly to the west of the Perak River and south of the Kuala Kangsar. It is composed of shale, sandstone and interbedded siltstone and shale (Foo, 1990). The shale is sometimes black in colour, due to small amount of carbonaceous material presence. A similar rock unit, Salak Baharu beds which is located in the Enggor Valley, south of Taiping, Perak, consists of grey to black carbonaceous shale interbedded with sandstone, calcarenites, chert and micaceous siltstone (Foo, 1990). No fossil was discovered in the beds, but Foo (1990) has assigned a late Palaeozoic age for both Kati beds and Salak Baharu beds, i.e. Devonian to Permian.

Away from Perak, to the north of the Kinta Valley, schist can be found in the central Kedah. Schist and phyllite made up one of the members of Jerai Formation which consists of non-fossiliferous metamorphosed detrital rocks. Another member of the formation is quartz arenite (Lee, 2009).

The Mesozoic sedimentary rocks are expected to be deposited on top of the Kinta Valley limestone, however there is no outcrop of this period. It is indicated that all the Mesozoic sedimentary rocks might have been weathered and eroded, or the basin might emerged to the atmosphere during the Mesozoic period and no sediments were deposited.

The nearby Mesozoic sedimentary formations could provide ideas about the depositional environment of the Kinta Valley after Palaeozoic times. Semanggol Formation is one of the Mesozoic rock units, which is composed of two major facies: a rudaceous-arenaceous facies of intraformational conglomerates and sandstone; and an alligo-arenaceous facies of rhythmically bedded sandstone and shale (Foo, 1990). This formation was deposited in a fore-deep basin at the leading edge of the Sibumasu and accretionary complex (Metcalfe, 2013) during Middle Permian – Late Triassic (Nuraiteng Tee Abdullah, 2009; Ridd, 2012). Three major outcrops of Semanggol Formation were discovered in Kedah and northwest Perak at regional-scale. All three outcrops were originated from the same single basin which now truncated by the wrench faults (Kobayashi et al., 1966; Burton, 1973, Ahmad Jantan et al., 1989).

2.2.3 Granite

The Kinta Valley is bounded by two major granitic masses: the Main Range and the Kledang Range. The Main Range located at the east side of the valley, and continuing northwards into Thailand and also southwards into Malacca. The Kledang Range is formed the western boundary of Kinta Valley, relatively small-sized compared with the Main Range and it gradually decreases in height from north to south, comes to an end on the west of Batu Gajah, southwest of Kinta Valley.

Main Range is composed of S-Type group of granitoids. The lithology near the margin of the Main Range, is a grey, medium grained, moderately porphyritic biotite granite, but porphyritic varieties are common (Ingham & Bradford, 1960). Non-porphyritic rock types such as microgranite have also been observed in the marginal area. In the Main Range province, the average age for the granite is 230-207Ma based on the results of Bignell & Snelling (1977) and Darbyshire (1988).

Kledang Range is formed by granite whose age ranges from Late Triassic to Early Jurassic. The granite is grey-coloured, medium grained, fairly porphyritic with biotite, but coarser and with a more pronunced porphyritic texture are more common at south of Ipoh (Ingham & Bradford, 1960). The radiometric datings of the Kledang Range granite, measured by Krahenbuhl (1991) appear to be within almost the same range, i.e. 213-198Ma (biotite) and 206-193Ma (muscovite), as the granite ages indicated by other workers.

The varieties of granitic rocks in the Kinta Valley, include porphyritic granite, microgranite, aplite, pegmatite and granite-porphyry. There is evidence that an earlier sedimentary cover on granite has been removed by erosion, and thus, the roof pendants of schist occur and found near Sungai Siput South and Sungai Choh, east of Tambun (Ingham & Bradford, 1960).

2.2.4 Alluvium

Alluvium covers broad area of the Kinta Valley plain including the stream valleys in the granite where it usually contains boulders and pebbles of granite and vein-quartz.

The depth of the alluvium varies (a few feet – over 70 foot) around the valley, and the average depth of the alluvium increases southwards towards the coastal plain (Ingham & Bradford, 1960). Four types of the alluvial deposits have been identified by Walker (1955), from the oldest unit to the youngest unit are, boulder beds, old alluvium, young alluvium, and organic mud and peat.

2.2.5 Geological Structures of the Kinta Valley

There is not yet any piece of work that well describes the regional structural history of the Palaeozoic limestone in the Kinta Valley. The previous workers who study the local geological structures may help to construct the regional structural history of the Kinta Valley.

Many isoclinal folds are presented mainly in the eastern half of the valley (Ingham & Bradford, 1960). However, recently some of these folds have been recognized as syn-sedimentary structures or slumps (Pierson et al., 2009).

The sedimentary rocks of the Kinta Valley have been tilted with strikes generally following the boundary of the nearby granite (Ingham & Bradford, 1960). The matching of the strike of the folds in the limestone with the outline of granite at the western side of the valley, suggest a normal intrusion (Ingham & Bradford, 1960). The Kledang Range considered as a granite horst (Gobbett, 1971), and eastern edge of the foothill is acted as normal fault plane. Gobbett (1971) also suggested the NW striking wrench faults have displaced this fault boundary and have resulted in the irregularity of the granite boundary.

Joints in the limestone and granite are too irregular to allow a solid interpretation (Ingham & Bradford, 1960). In the early seventies, lineament study on aerial photography of Kinta Valley done by Gobbett (1971) defined a consistent pattern of fracture's orientation. The dominant fracture sets are striking NW-SE and ENE-WSW, and indicating a rough E-W compression.

Faulting is widespread in rocks of the Kinta Valley. Two types of faults have been found: shear faults and tension faults. Shear faults are caused by compression, and were moving parallel to the strikes of the beds or actually on a bedding plane oriented approximately to the north (Ingham & Bradford, 1960). Tension faults have been recorded in many localities where quartz vein or aplite has invaded the sedimentary rocks near to the granite contact. The faults usually have steep vertical dips and the displacement is small (Ingham & Bradford, 1960). An example of slickensiding in granite showing mylonitic features has been observed near Chenderiang, Bujang Melaka (Ingham & Bradford, 1960).

2.3 Hot Springs

Hot spring area exhibits high variability in rock permeability, composition, structure, and available surface water. Generally, a hot spring has a temperature noticeably above the mean annual air temperature in the locality, and a preferential conduit for flow, such as a fault or fracture plane, must be present in the subsurface to bring this water up.

At least 45 hot springs in Malaysia have been recorded, and the occurrence of the discovered hot springs in Peninsular Malaysia shows a distinct pattern which is considered to be structurally controlled and probably genetically related to granite intrusion and post magmatic activities (Abdul Rashid Bachik, 1991). Most of the discovered hot springs are located either at/near the granite masses, or along the major fault or shear zone (Abdul Rashid Bachik, 1991; Abdul Rahim et al, 1997). Some of the hot springs formed on the sedimentary rock near to the granite contact. The heat of the hot springs is believed to be supplied by the granite batholiths beneath the earth which is not completely cool down yet and continue dissipated the heat to surrounding. Another option is to have a thermal re-heating event. The radioactive decay of the elements such as uranium inside the rock can also be the heat source for the hot springs. The deep-lying groundwater heated up by the granite masses, seeping through the fractures/faults in the crust and moving upwards, eventually emerged on the surface of the earth, formed as a hot spring.

A few hot springs have been recorded by previous workers in the Kinta Valley, such as Ayer Hangat in Tambun, Kramat Pulai, Sg.Periah and Tasek Railway Station

(Ingham & Bradford, 1960). The hot spring in Tambun (Figure 2.3) is the most famous of these springs. It has now been commercialized and is at the heart of a resort, named the "Banjaran Hotsprings Retreat". The springs flow from a small area next to the foot of a limestone cliff; hot water rises from the limestone and forms some pools. The temperature of the hot spring main source recorded at the surface was 66°C on 1951 (Ingham & Bradford, 1960) and is still the same today. There is no smell of hydrogen sulfide near the spring.

Kramat Pulai's spring was an underground hot spring and was tapped during mining in 1933, at about 90 feet below ground-level. The temperature of the spring at the point of emergence was 50.5°C (Ingham & Bradford, 1960). No trace of this spring can be found at the surface.

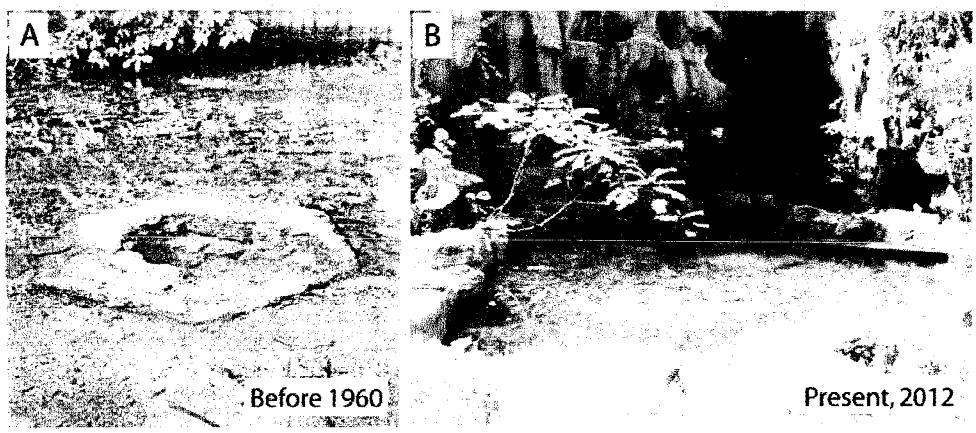


Figure 2.3 Hot springs located at the limestone foothill in Banjaran, Tambun. [A] In the past (Photograph B.H. Flinter, from Ingham & Bradford, 1960). [B] Present.

CHAPTER 3

METHODOLOGY

3.1 Multi-scale Tectonic Analysis

The information on the tectonic indicators (e.g. strike and dip of bedding, fractures, joints, fault, etc) have been collected from satellite images (mega-scale), outcrop, hand specimens (meso-scale) and thin sections (micro-scale) (Figure 3.1). These data were divided into groups according to their characteristics and checked for cross-cutting relationships in order to construct the tectonic evolution of the area. Relative chronology criteria are essential to decipher such a tectonic history. Fault kinematics are deduced from standard criteria using striations/slickensides.

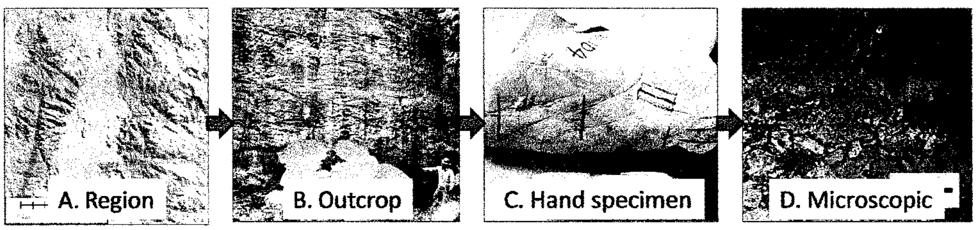


Figure 3.1 Multi-scales of analysis composed by (A) mega-/regional-scale, to meso-scale: (B) outcrop- and (C) hand specimen-scale, and also (D) microscopic-scale.

Other unconventional methods used to investigate the deformation of the rock and to map the lithologies, include satellite imagery analysis which provide an overall view of the region and helps in preliminary decision making of the study; palaeo-magnetic analysis which is the study of the anisotropy of magnetic susceptibility (AMS) of the rocks that reveal the rock deformation at microscopic-scale. In order to reveal the regional palaeo-structural activity, all the results from the analysis of different scales, will be integrated and divided into categories.

3.1.1 Regional-scale Analysis

From a regional-scale analysis, a tele-interpreted textural map was constructed by draping satellite image SPOT-5 with resolution of 2.5m onto digital elevation model of SRTM (DEM, resolution 90m) (Jarvis et al., 2008) (Figure 3.2). The texture map was carefully analyzed to discover the meaningful geomorphic features such as fractures/faults, bedding traces, folds and lithologies. All the interpreted structures or features were later systematically checked in the site if accessible.

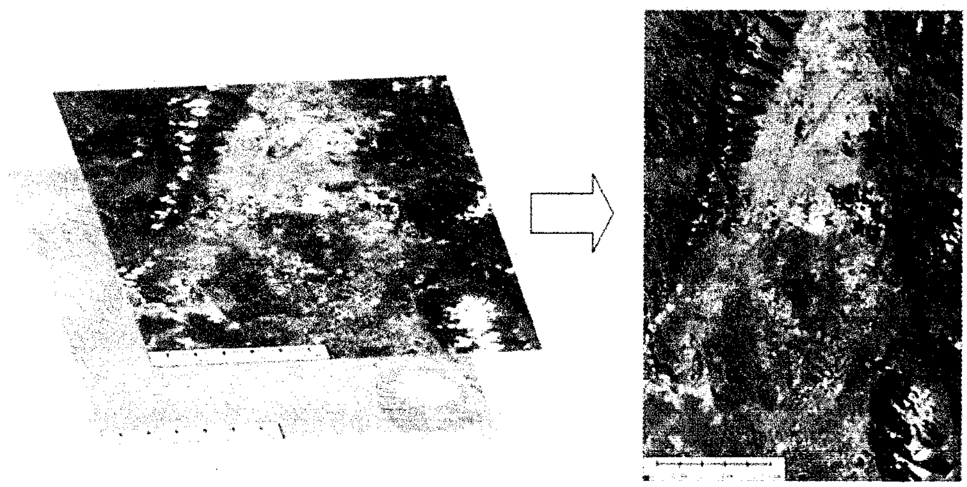


Figure 3.2 The satellite image, SPOT-5 (left top), draped on top of DEM of SRTM (left bottom) can generate a texture map (right) which shows contrasting features and allow us to make further interpretation in detail.

Drainage pattern can be defined as geometry arrangement of rivers that naturally formed in a network in a particular area (Ibrahim Komoo et al., 1989). Drainage analysis is useful in structural interpretation, particularly in low relief areas (Howard, 1967; Deffontaines et al., 1992). It affected by factors such as types, distribution and location of the lithology at the surface; and/or arrangement of the weak plane on rock like bedding plane, fault, joints, folds, etc. Streams and rivers are traced out from the maps of the Kinta Valley (Ingham & Bradford, 1957a; 1957b) in order to reveal the hidden geological information which cannot be easily resolved by satellite images and outcrops. There are several major drainage patterns and their characteristics have been summarized in the Table 3.1 (Howard, 1967).

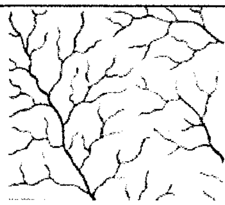
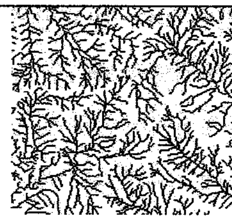
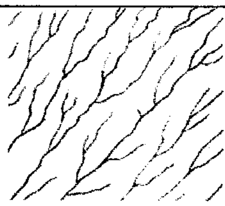
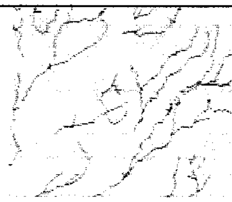
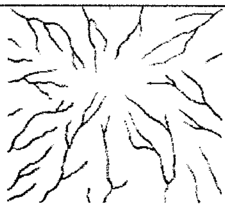
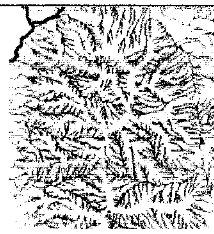
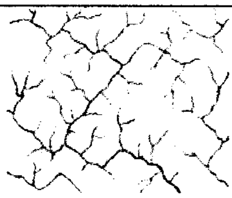
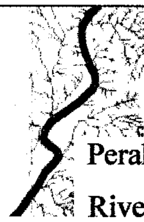
Most of the surface within Kinta Valley is covered by the recent alluvium and the rivers flow on top of them. The underneath bedrocks are hidden by sediments, causing difficulties to study the rocks directly. In such case, the drainage analysis will be useful to provide the subsurface information. The river always tend to flow in the shortest path to the shoreline according to the regional slope formed by the smoothing the topography (Deffontaines et al., 1992), but if the rivers not do so, it is a drainage anomaly and it probably influenced by the local geological structures, topographic anomalies or other external factors (Pubellier et al., 1994).

Some criteria for selection of these anomalies (Pubellier et al., 1994) are:

- Local modifications of the drainage pattern: the drainage is locally appeared in a certain pattern which is not the same as the major one, such as radial drainage pattern included centrifugal and centripetal (Howard, 1967).
- The wide angle of river's convergence, which the normal convergence is usually 60°. Divergence of the stream indicated an underground topographic high.
- Flow directions are not followed the regional slope.

The granite is the competent lithology which commonly highly fractured usually initiated by the tectonic event. It is worth studying these fractures to understand the deformation. Numerous significant lineaments or deep narrow valleys of the granites can be easily recognized in the DEM. After all the fractures are recorded, they will be grouped according to their azimuths or strikes into categories in every 10°, from 270° to 089° (270°-279° ; 280°-289° ; ...; 080°-089°) in clockwise direction, and plotted on the rose diagram. The major fracture sets in the granite will be compared to other scales and lithology, to understand the relationships. Due to the uneven distributions of the fracture patterns in this region, four zones around Kinta Valley have been selected (Kledang Range and three zones of Main Range), and studied separately.

Table 3.1 Descriptions of drainage patterns and corresponding examples found in Kinta Valley

Name and Descriptions	Drainage patterns	Examples
Dendritic • Appearance likes branches of the tree • Commonly developed in the homogeneous bedrock e.g. granite • Generally not affected by the geological structures		 Kledang Range
Parallel • Streams are almost parallel to each others • Regional slope, or affected by the major faults or joints		 Gopeng - Kampar
Radial • Controlled by the geological structures • Centrifugal: dome structure such as volcano cone • Centripetal: depression area or basin		 Bujang Melaka
Rectangular • Streams are developed in right angle. • Commonly controlled by the joints and faults		 Perak River

3.1.2 Outcrop-scale Analysis

In order to verify the remote observation, geological data collection was conducted on the various outcrops. Outcrops were chosen on the basis of accessibility and presence of significant geological structures. The geological data and hand specimens were collected in the selected sites. Dominant strike and dip measurements of fractures and bedding as well as crosscutting relationships and fracture-filling materials, were recorded (Figure 3.3). Kinematic indicators such as slickenside fabrics and marker-bed offsets were noted in detail, because they are essentially important in reconstructing the palaeo-kinematics.

The major geological structures like bedding and faults, were digitized and stored in geo-database as GIS layer for integrated study. The collected fracture data were processed using the "Stereonet" software (Cardozo & Allmendinger, 2013). All data were plotted on a lower hemisphere, equal-area projection, and were used to compute the palaeo-stress field for each deformation event.

Geological mapping around the hot spring area, accompanied with previous result of interpretation in satellite image, is used to detect the potential geothermal area. Infrared satellite images (Landsat 7 – band 6, 30m resolution) was used to reveal the locations of high-temperature geothermal area in Kinta Valley. The hotter spots show brighter colour in the Landsat image. Based on this, two potential geothermal areas were checked in the site, to confirm the existence of the hot springs. Unfortunately, all the potential spots with high thermal signals are not related to natural geothermal source, but are rather related to human activities (Figure 3.4).

Figure 3.3 Strike and dip of the fracture plane measured and recorded for the further interpretation and study.

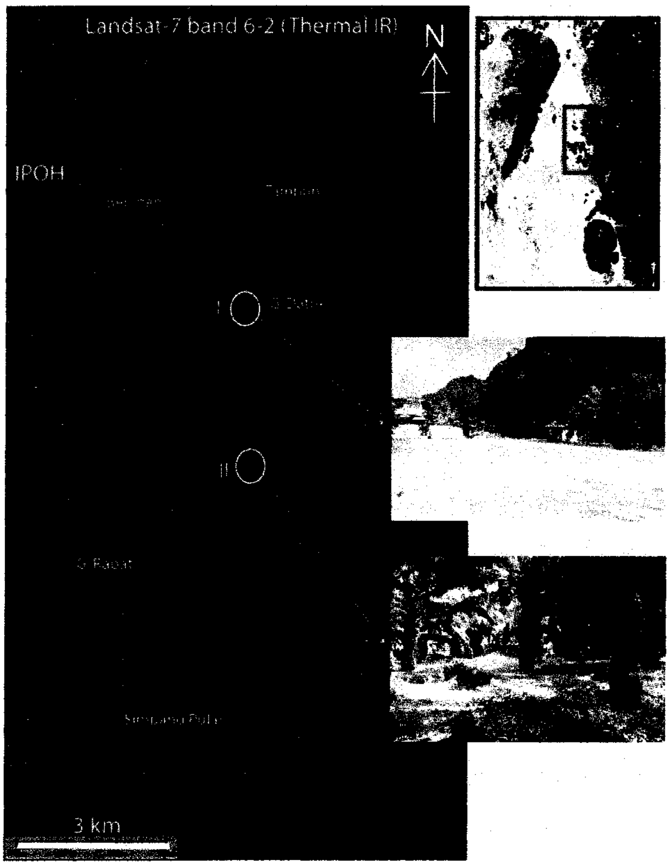


Figure 3.4 Regional investigations for the potential hot spring's location using Landsat-7 image. Two localities, I and II marked by circles, selected in the Landsat-7 image in the IR (Infrared band). No sign of hot springs were found in those localities. Small inserts show the views of the selected localities respectively. Locality I located in a Chinese temple and locality II situated in oil palm farm.

3.1.3 Hand Specimen-scale Analysis

Analysis of the oriented hand specimens was done in the laboratory. The purpose of this analysis was to reveal the tiny fracture trends which are difficult to observe and measure their orientation. The hand specimens were cut in a way to obtain a 3D view of fractures and improve the measurement accuracy of fracture orientation. The cutting of the hand specimens (Figure 3.5) was perpendicular to bedding because the maximum or minimum principal stresses are generally horizontal and parallel to it, and causes fractures to be inclined relative to the layers.

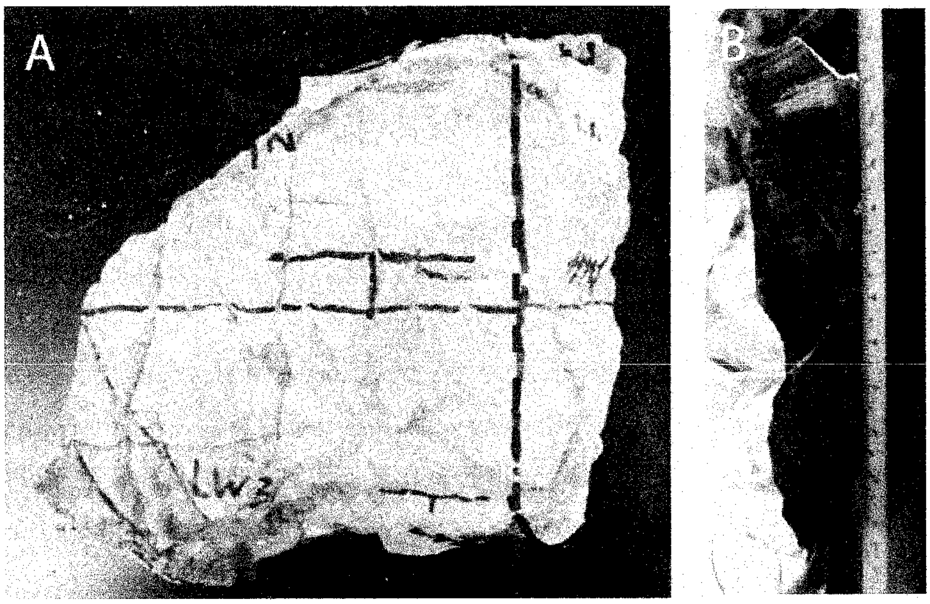


Figure 3.5 The tiny fractures on the hand specimen were observed and measured in laboratory. [A] Hand specimen collected from an outcrop, red dash line represents the cross section in B, where [B] the true strike and dip of the tiny fracture plane is determined.

3.1.4 Microscopic-scale Analysis

The microscopic analysis was conducted using thin sections and anisotropy of magnetic susceptibility (AMS) in the rock.

For the tiny fractures or structures in the rock which are hard to see with naked eye, those samples were make into thin section to observe at microscopic-scale. The orientations of the samples are carefully transferred to the thin sections, so that the direction of the structures or the deformation in the sections can be deduced later.

AMS is defined as the variation in direction of the principal magnetic susceptibility axes within a rock sample. The shape and alignment of the magnitude ellipsoid represents the preferred alignment of ferromagnetic crystals during the emplacement of a magma body or crystal growth or realignment in a stress field (Ellwood, 1978). AMS analysis has been conducted in order to obtain the 3D microscopic deformation in the rock. The rocks affected by different degrees of the deformation, which show various attitudes of beddings, were selected for the palaeo-magnetic study. AMS fabric has also been used to interpret major stress directions in metamorphosed rocks (DeFrates et al., 2006) and lava flow direction.

For anisotropy of magnetic susceptibility (AMS) analysis, rock sample were collected and marked with orientation. The oriented hand specimens with dimension around 15cm x 15cm x 15cm, are collected from a site, in order to guarantee that enough samples (six and above) can be produced. Samples must be fresh and un-weathered because surface weathering oxidizes magnetite or hematite with attendant deterioration of Natural Remanent Magnetism (NRM). The orientations of beddings have to be determined so that the structural corrections can be applied. The oriented rock sample will be cored in the laboratory to obtain individual cores (samples) with diameter of 1 inch or ~2.5 cm. The orientation of the rock samples will be carefully transferred to each cores or samples. Specimens (pieces of samples) are prepared with appropriate dimensions (length = 2.2 cm) for NRM measurement. This procedure may provide more homogeneous result. A typical specimen has volume of ~10cm$^{3.}$

Each sample must be able to provide an unambiguous in situ geographic orientation. Butler (1992) used the right-handed Cartesian coordinate system as orientation scheme for cored sample, as illustrated in Figure 3.6. These specimen coordinates axes were used in laboratory measurement.

NRM are in vector direction, which is described in terms of inclination, I (with respect to horizontal at the collecting location), and declination, D, (with respect to geographic north). The usual procedure is to view the NRM direction as radiating from the centre of a sphere and to display the intersection of the NRM vector with this sphere, e.g. equal-angle projection and equal area projection.

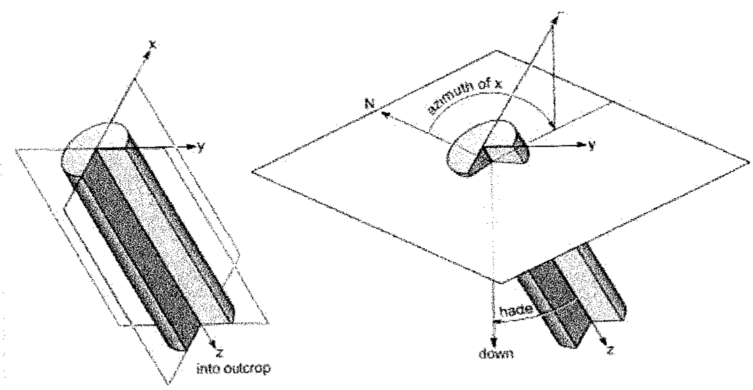


Figure 3.6 The definition of the orientation system for palaeo-magnetic cored sample. The z axis is the core axis (positive z into the outcrop), the x axis is in the vertical plane (orthogonal to z), and the y axis is horizontal. In the field, sample orientation is determined by measuring (1) azimuth of the horizontal projection of the +x axes (azimuth of x-z plane) and (2) hade (angle from vertical=90°-plunge) of the +z axes.

Five representative specimens from the limestone around the Kinta Valley that were collected at gradual distance away from the granite were chosen for preliminary assessment of magnetic fabric (anisotropy of magnetic susceptibility, AMS). Using a Bartington MS2B single sample dual frequency sensor, the specimens yielded very weak magnetic susceptibility values that ranged from 0.05 x 10^{-6} to 0.14 x 10^{-6} SI units, reflecting very low content of para- and/ or ferromagnetic carriers . Such low values were found to be too close to the instrument noise level (0.1×10^{-5} SI) and were discarded as unreliable to use for further magnetic fabric assessment. It was therefore unfortunate to decide not to use this useful technique for assessment of the petrofabric variations within the studied limestone as it was hoped to.

3.2 Field Work, Mapping and Sampling

Reconnaissance survey followed by fieldworks were conducted to collect geological data and to validate the interpretation made from satellite image. The ambiguities that occurred while the interpretation was made on the satellite images, were verified in the field to refine the interpretation. It enabled to reconstruct a more precise and reliable structural history. The characteristics of the prominent fracture sets on the outcrop such as strike and dip of the fracture planes and the beddings, will be recorded. The readings of the bedding planes are important for the correction especially when the bedding is steeply dipping.

Mapping was conducted using satellite images and outcrops. The information of the map included lithology distribution and geological structures. The drainage map was employed and studied in detail, to deduce the geological information of the alluvium plain in the middle of the valley, which are lacking in the previous geological map. The data extended into subsurface able to illustrate the geology beneath the surface. The subsurface illustration was presented in the cross sections.

Two types of sampling were carried out in the study; the first one was the sampling of the oriented hand specimen (Figure 3.7) for the tiny fracture's observation, making thin section, and to study the microscopic fractures. The second sampling related to the AMS analyses. The collected hand specimens were big enough to produce at least 6 cores with 1 inch diameter. The dimension of the hand specimen blocks are about 15cm x 15cm x 15cm. After the coring was done, the orientation of the hand specimen was carefully transferred to the cores. Every core can be cut into specimen (like core plug) with length of 2.2 cm, and it probably can give more consistent results with more specimens.

Figure 3.7 Rock sample is taking out from the outcrop.

CHAPTER 4

RESULTS – OBSERVATION AND ANALYSIS

4.1 Regional-scale Observation and Analysis

There are a lot of geological information that can be extracted from a satellite image and digital elevation model (DEM) based on their colour, shape, texture, jointing, drainage pattern, etc. These characteristics are controlled by the physical and chemical properties of the rock or even human activities. From the satellite imagery used in the study, interpretations were made and they were counter checked in the field, to make sure the authenticity of the interpretations. The identification of lithologies and structures, from the satellite imagery were the main focus of the study. Furthermore, the study enabled to generate cross sections more accurately, in order to understand the geology of the Kinta Valley.

4.1.1 Aerial Observation

An aerial survey that covering Gunung Rapat, Simpang Pulai and Gunung Datok, Tambun, have been carried out by a helicopter. The purpose of the aerial observation was to obtain a regional view of the geological structures, which enabled to correlate and refine the results and interpretations made from outcrops and satellite imagery. It is easy to identify the mega-structures from high altitude, for example the large fractures or valleys in Gunung Datok (Figure 4.1). Similarly, the vertical limestone beddings adjacent to the granite and the bedrock are underlined by narrow valleys, and have been conspicuously observed. The aerial observation and interpretation of the limestone in Gunung Datok indicates that the beddings have been tilted, and formed anticlines and synclines as a result of shortening (Figure 4.2).

Figure 4.1 NW-SE trending valley cut through the middle of Gunung Datok. This valley may have been originated from the high dipping fracture or fault. Valley is marked with a red line.

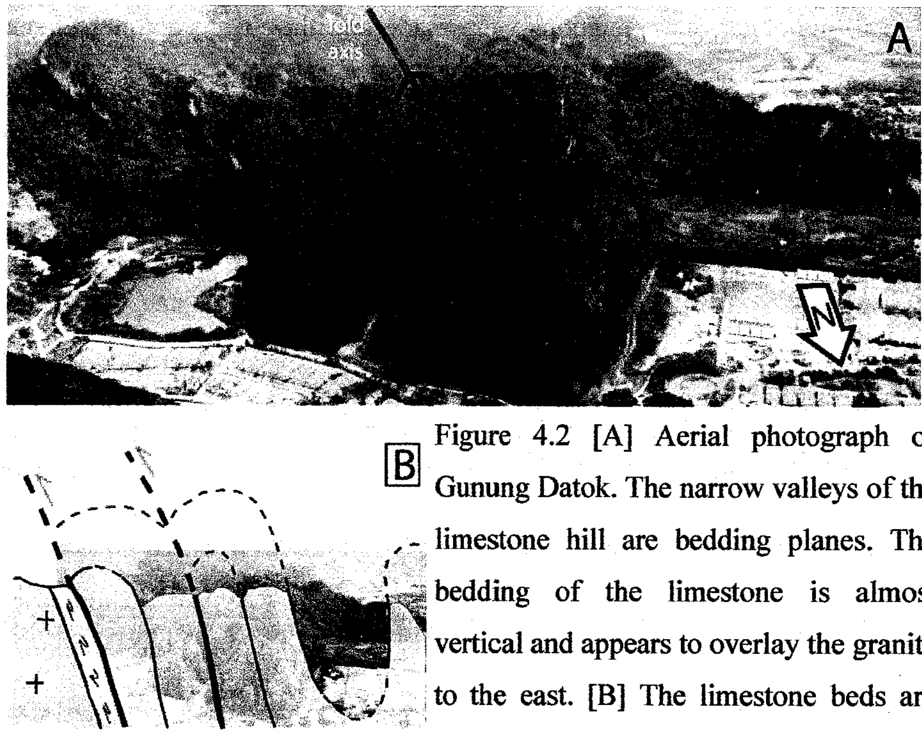


Figure 4.2 [A] Aerial photograph of Gunung Datok. The narrow valleys of the limestone hill are bedding planes. The bedding of the limestone is almost vertical and appears to overlay the granite to the east. [B] The limestone beds are interpreted to be folded and formed tight anticlines and synclines.

4.1.2 Satellite Image (SPOT-5) and Digital Elevation Model (DEM)

Satellite image and DEM are useful in identifying the lithologies and structures, based on the texture, drainage patterns, fractures/joints patterns, vegetation, relief and other characteristics. All the discovered lithologies and structures from the satellite image and DEM are stated below.

4.1.2.1 Lithologies

Granite

There are high topography terrains located in the east and west flanks of the Kinta Valley. The high relief (average altitude > 1000 m) in the east and west of the Kinta Valley shows massive and homogeneous topography (Figure 4.3). The massive rock body existed because of the lithology which contains the minerals which are resistant to weathering. The high relief area has steep sides, and covers a large area which can reached 1000 km^2. Dendritic drainage pattern is dominant in this area. Strong joint patterns are also common. The fractured rocks are highly competent and underwent brittle deformation. The round shape topography of the intrusion has been observed in Kampar (Bujang Melaka) (Figure 4.3A & B), it is likely to be an individual intrusion. All the aforementioned characteristics indicate a granite province, which contains high percentage of weathering resistant mineral such as quartz, and it occurred as a massive body that stand out in a high relief manner. With the uplifting process, batholiths became mountain ranges, like the one observed in the Kinta Valley.

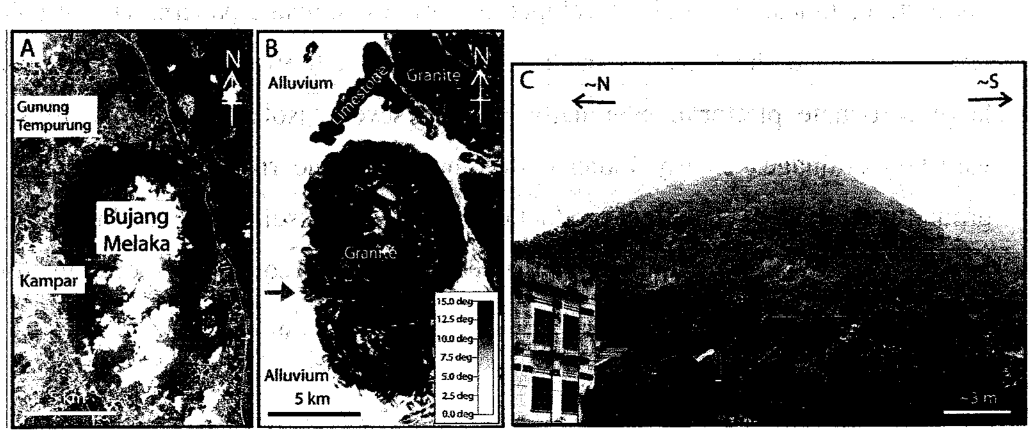


Figure 4.3 Granite intrusion, Bujang Melaka, situated in the SE part of the Kinta Valley, and the limestone hill, Gunung Tempurung, located at the north of it, shown in the satellite images, [A] SPOT-5 and [B] digital elevation model (DEM) of SRTM. [A] Dark colour on the intrusion represents the thick vegetation. The white clouds are commonly formed on top of the peaks of the intrusion due to high altitude. [B] DEM with slope shader (the colour variation shows the steepness of the slope). The darker shade indicates steep slope, whereas white thin lines depict fractures. The white shade around intrusion is the flat alluvium plain. Red arrow pointed out the location of C. [C] Outcrop view of granite in Kampar.

Limestone

In the valley, especially at the foot of the Main Range granite, there are numerous small, high relief and isolated hills which have steep sides and stand out from flat plain (Figure 4.4), it can be clearly observed in slope shader of DEM. These terrains have elevation ranges of a few hundred meters. The area of each terrain is relatively small compared to the granite, and each covered less than 20km^2.

Some of the fractures are well developed in this terrain, but less intense compared to the granite. Simple drainage pattern presents in the area. The drainages on the surface usually developed on the sides of the terrain, sometimes cutting through the terrain or even vanishing at the contact with this terrain. This terrain is occupied by a limestone, a lithology that can easily dissolved by water. Because of the intense dissolution, limestone rarely developed a complex drainage pattern. The dissolution always followed the fractures in the limestone, and formed the steep cliff, cut the large carbonate platform, eventually become several isolated limestone hills. The vanished drainages clearly indicate the capture of the rivers with the subsurface groundwater system. The final product of this intense dissolution of the limestone will be karsts such as caves, dolines, sinkholes, etc., which commonly occur in tropical area.

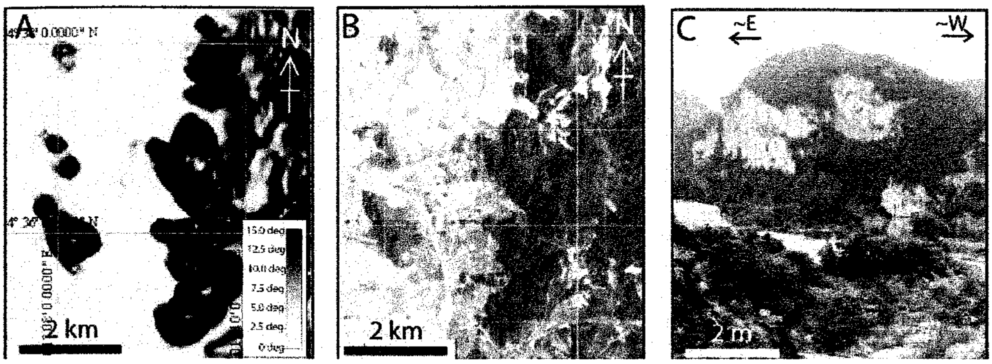


Figure 4.4 Limestone hills around Tambun, eastern side of the Kinta Valley. [A] Digital elevation model (DEM) of SRTM. The steep cliff of the limestone hills are highlighted by the DEM with slope shader. The limestone hills are commonly marked by black-coloured, isolated terrain, caused by the steep slopes in all the sides of the hills. The other lithology marked by the dark shade, to the east of the isolated hills, is the granite. The boundary between limestone and granite can be identified by a narrow depression formed between two different gradients of the slope of the terrains. [B] The outlines of the limestone hills can be clearly observed in the high resolution (2.5m) satellite image, SPOT-5, and without urban development on top. The limestone outline is sometimes controlled by major joints or faults. The red arrow pinpoints the outcrop shown at C. [C] Limestone hills with steep slopes have been observed near to the granite-limestone contact.

Schist and Shale

Another type of terrain with homogeneous and low relief is found, and it just slightly higher than flat alluvium plain (Figure 4.5A). The sizes of the terrain exposed to the subaerial vary and may cover only a few km^2, or reach tens of km^2 which found in the southern part of the valley. Jointing is not strong in this terrain, may indicate that the lithology is incompetent. This terrain covered by thick vegetation.

It also shows dendritic drainage pattern which is similar to the drainage network observed in the granite (Figure 4.5B). The drainage is well developed and suggests that it has low permeability property, as the rock is not permeable enough to allow the water to infiltrate into the subsurface. Although stream and river are less affected the erosion of the terrain, but the terrain still experienced high erosion because of composition of the rocks may be mainly fine-grained material.

Low relief topography of this terrain has resulted in strong erosion. The texture on the DEM shows that this province is composed of interbedded beds with different competency and resulting from various erosion degrees. The different degrees of erosion of rocks have formed the short ridges and troughs, which likely represent the beddings or foliation of the rocks. The short ridges can be connected and to identify the trend of the beddings, also to reveal the hidden structure, such as dome which has been identified in this case (Figure 4.5C). The lithology of this terrain is carbonaceous schist or highly deformed carbonaceous shale. It has been verified in the field (Figure 4.6).

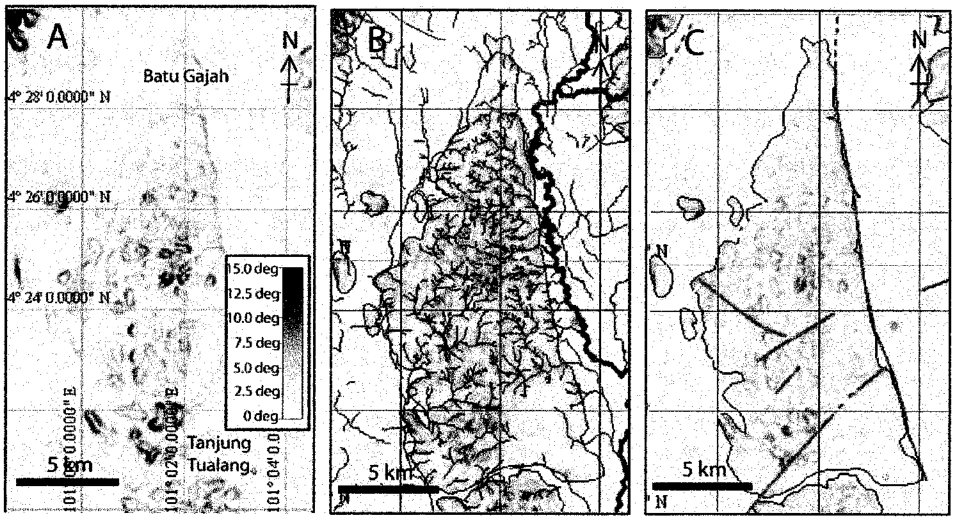


Figure 4.5 Schist exposures at Batu Gajah, western part of the Kinta Valley. Green: schist; pink: granite; blue line: river; lithologic ridge: yellow dash line; red line: fault [A] DEM indicating low relief terrain. [B] Drainage pattern with major flowing direction to the east and west, shows that this terrain is rising zone with N-S axis. [C] Lithologic ridges in DEM have been connected (marked by yellow dash lines), it revealed the schist beds have been folded. This terrain is folded and uplifted, as indicated by an anticline.

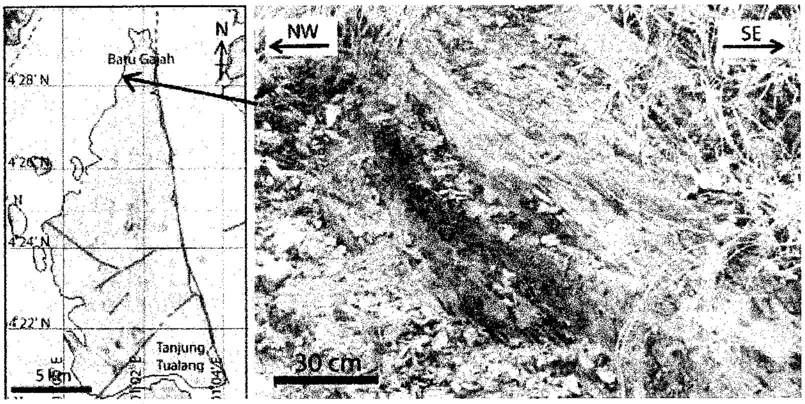


Figure 4.6 The arrow on the left map depicting a deformed shale or schist in Batu Gajah. Part of the outcrop appears black in colour, and is carbon-rich.

Clastic sedimentary rocks

Clastic sedimentary rocks such as sandstone and mudstone are found in Seri Iskandar, southwest part of the valley (Figure 4.7). These rocks are commonly highly weathered except for the sandstone. The clastic rocks are striking in nearly N-S and highly dipping, which similar to the limestone beds in the Kinta Valley. The brittle deformation resulted intense fractures on the rocks. The N-S ridges are observed in the DEM. It most probably represented the hard rock (e.g. sandstone), which is resistant to weathering. The narrow and steep flanks of the ridges indicated that the rocks are highly dipping.

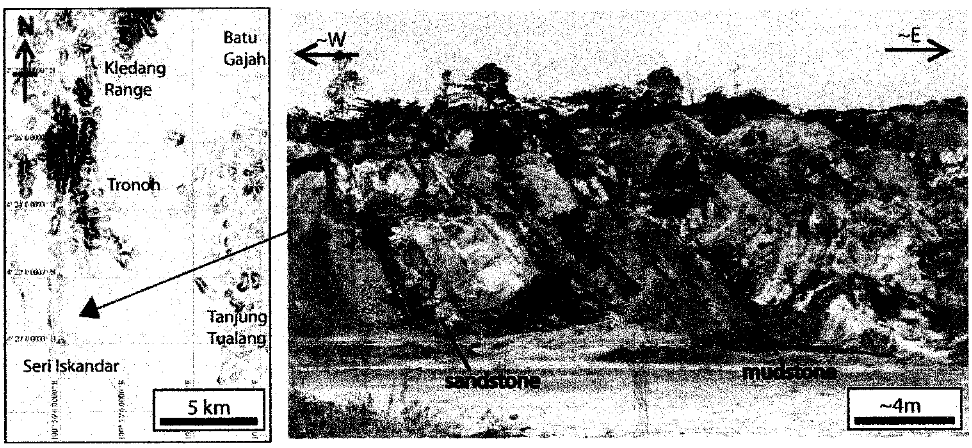


Figure 4.7 Interbedded sandstone and mudstone observed in Seri Iskandar. The outcrop may extended to the north, connected to the N-S trending ridges (elongated dark area to the west of Tronoh) located at the west part of the map. The ridge probably composed of massive, quartz-rich sandstone, resistant to weathering.

Alluvium plain

The alluvium plain is a low relief area and lacks the obvious geological features to be recognized it in the satellite image (Figure 4.8A). It composes recent sediments which are the accumulation of the un-consolidated sediments weathered from the surrounding rocks such as granite, limestone, schist, etc (Figure 4.8B). The sediments have been transported by rivers and streams, and deposited where the transporting ability of the flow is low.

No particular drainage pattern developed on the alluvium plain. It can be either a simple drainage such as straight river, or a more complicated network, like, sinusoidal and rectangular pattern. Mostly, the particular drainage network or drainage anomalies formed on the alluvium plain reflected the lithology or structure of the bedrock such as major faults or joints, anticline, syncline, etc.

4.1.2.2 Geological Structures

Structural interpretation on the satellite image is important for the regional tectonic study. It reveals the mega-scale geological structures which are not easily seen in the field. The purpose of the interpretation is to acquire the information about the altitude and the distribution of a rock layers or horizons, and it leads to logical conclusion of relationships between various structures and lithologies. Thus, several geological structures or information such as, bedding traces, folds, faults and lithologic ridges are revealed.

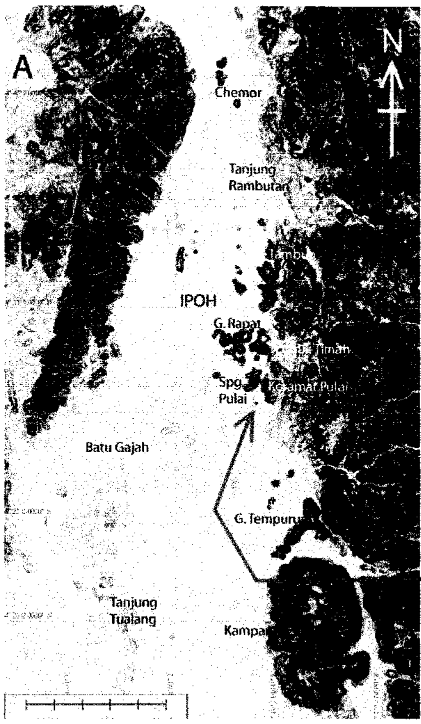
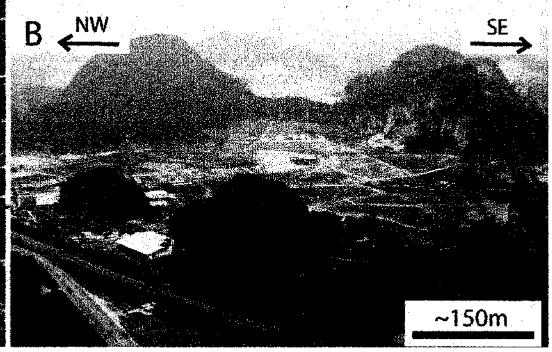


Figure 4.8 [A] The DEM with slope shader reveals a very gently sloped area such as alluvium plain, where marked by white colour. It is mainly located at the middle of the valley. [B] The flat alluvium plain is distributed around the limestone hills.



Beddings/bedding traces/foliations

In certain conditions, the bedding or foliations of the rock can be detected in the aerial photograph and/or satellite image, e.g. valleys, ridges and troughs. The bedding planes and foliations are naturally weak zones which facilitate flow of solvent, and sometimes leave narrow valleys in the limestone hill. But some of the narrow valleys represent fault lines, especially those lineaments which are straight and long for few kilometers. The bedding traces can be used to interpret geological structures such as fold by observing the changes of the strikes of the beddings, e.g. Gunung Datok (Figure 4.9).

The bedding of the limestone in the Kinta Valley is almost vertical and dipping to the west close to the granite contact, e.g. Gunung Datok, Tambun and Gua Tempurung, Gopeng.

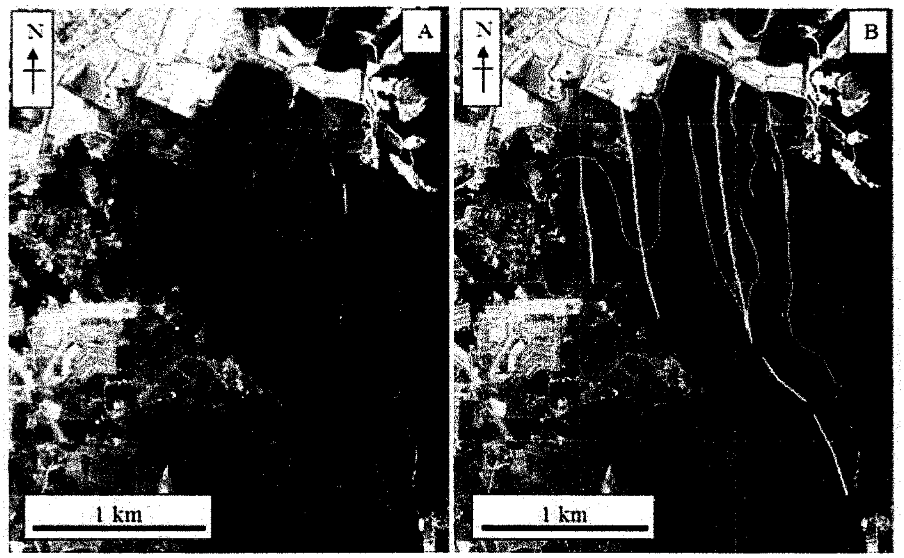


Figure 4.9 Bedding traces found in the limestone hills, Gunung Datok, Tambun, have revealed the striking of the limestone beds. The turning of the strike line indicates a fold structure. Yellow lines: bedding traces; green lines: fold axis; red lines: faults. [A] Before interpretation. [B] After interpretation.

Folds

A fold is formed when a rock strata is subjected to compression. It is most likely occurring in the strata which are ductile and/or the confining pressure is high. The main classes of the folds are anticlines and synclines. Folds can be interpreted from the distribution of the bedding, river's profile, topography, distribution of the surficial sediment and others. The orientation and symmetry can be highly different. The plunge represented the inclination of the fold which sometimes can be determined by detail geological mapping or from the observation of the satellite image. Domes and basins are structures which are associated with folding.

Fold axis is the intersection of the axial plane with the bedding plane (Figure 4.9B). The turning of the bedding traces indicates a fold or even its axis, which identified by joining all the bedding traces.

The vertical limestone in the Tambun area is probably the remnant of the tight folds that located beside granite intrusion (Figure 4.10). The limestone has not been cut by the granite like a usual intrusion, but likely uplifted by granite. Tight folds are formed due to the strong compression/collision between limestone and asperities which probably the uplifted granite intrusion. The compression shorten the limestone in folding way, and just few kilometers away from the asperities (intrusion), the bedding of the limestone is still remain gently dipping. The competency of the limestone caused the tip of the fold to be easily broken, which make the limestone beds do not have complete bending feature anymore, so it is too hard to directly observe in the satellite image.

Several folds have also been discovered in the satellite image and DEM. The appearances of these folds are commonly long ridges with steep flanks in DEM, whereas it can be detected when the strike lines or lithologic ridges of bedding are varying in the satellite image. These folds are formed in the different lithologies in the southern part of the Kinta Valley, which are situated in limestone hill, Gunung Tempurung, Gopeng; schist of Batu Gajah and Tanjung Tualang; and sandstone and mudstone of Seri Iskandar, Tronoh.

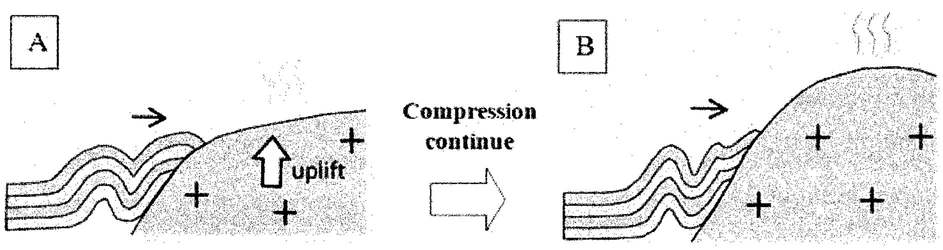


Figure 4.10 Cartoon illustrating the formation of tight folds in Tambun. [A] The limestone contacted with the uplifting hot intrusion, and began to fold. The intrusion does not crosscut the limestone. [B] After a period of compression, and as the intrusion raises the limestone continues to fold tighter as observed in the area of interest.

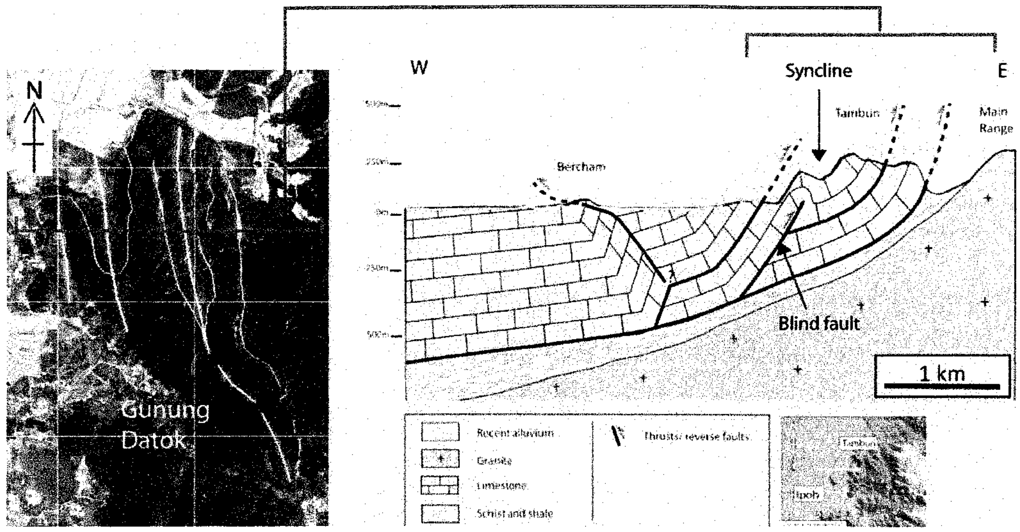


Figure 4.11 The proposed cross section for the tight folds that found in Gunung Datok, Tambun. The tight folds are believed to be initiated by the thrust faults. There is a blind fault that initiated the syncline.

Faults

Normal faults and thrust faults are found in the Kinta Valley. Normal faults are represented by the long negative lineaments or valleys, due to its highly dipping (Figure 4.12A). At the regional-scale, the normal faults are not completely straight, but show a curvature profile. The large normal faults normally marked by the major drainage on the surface, with fault plane gradually flattening at subsurface in a spoon-shaped manner.

The triangular pieces representing thrust imbrications within a small wedge can be observed in the satellite image (Figure 4.12B). It occurred in limestone hill of Tambun and propagated towards the granite to the east.

Lithologic ridges

The short, narrow and nearly parallel ridges found in the DEM (Figure 4.5A), are referred as lithologic ridges. The formation of the lithologic ridges can be caused by the intense erosion of the softer part of the highly dipping interbedded rock units, e.g.

interbedded hard sandstone and soft mudstone, and which left the harder part of the rock units with the ridge appearance.

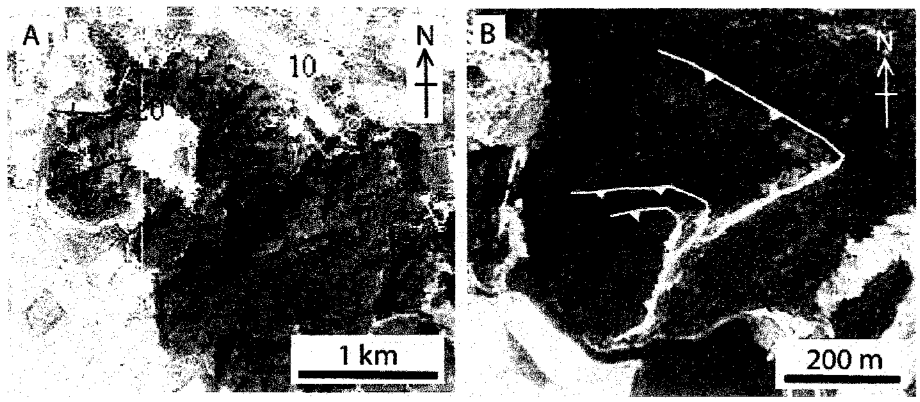


Figure 4.12 [A] Topographic steps created by a series of normal faults (red lines). It caused the limestone hills to gradually lower towards the northwest. [B] The triangular pieces (yellow lines with tooth) found on top of the limestone hill. These structures are thrust imbrications which propagated towards the east.

Roof pendant (HT) occurred in the limestone in Gua Tempurung

The limestone of the Gunung Tempurung, southern part of the Kinta Valley, appears to have 'T'-shape. Gunung Tempurung located close to the granite, Main Range to the east and Bujang Melaka to the south (Figure 4.3A & B). From the observation in the satellite image, the current appearance of the limestone is probably related to the intrusion of the Bujang Malaka.

The scenario is proposed to explain the mechanism that caused the T-shaped appearance of the limestone hill. The estimated rock units of the Kampar area, from oldest to youngest are: Proterozoic or Early Palaeozoic rocks, schist or shale, limestone, post-limestone sequences and volcaniclastic rocks produced by the volcano in the arc. The E-W compression induced the thrusts in the limestone of the Kinta Valley and the rock units above it. The thrust planes on the surface of the intrusion with the schists or shale acted as the decollement layer (Figure 4.13, 4.14). When the granite is intruded, the limestone sit directly on top of the intrusion and has gradually been uplifted. As the intrusion getting higher, the limestone laid on the intrusion at a steep position, which likely to slide down from the slope due to gravity, just like normal fault or roof pendant (Figure 4.15 and 4.16).

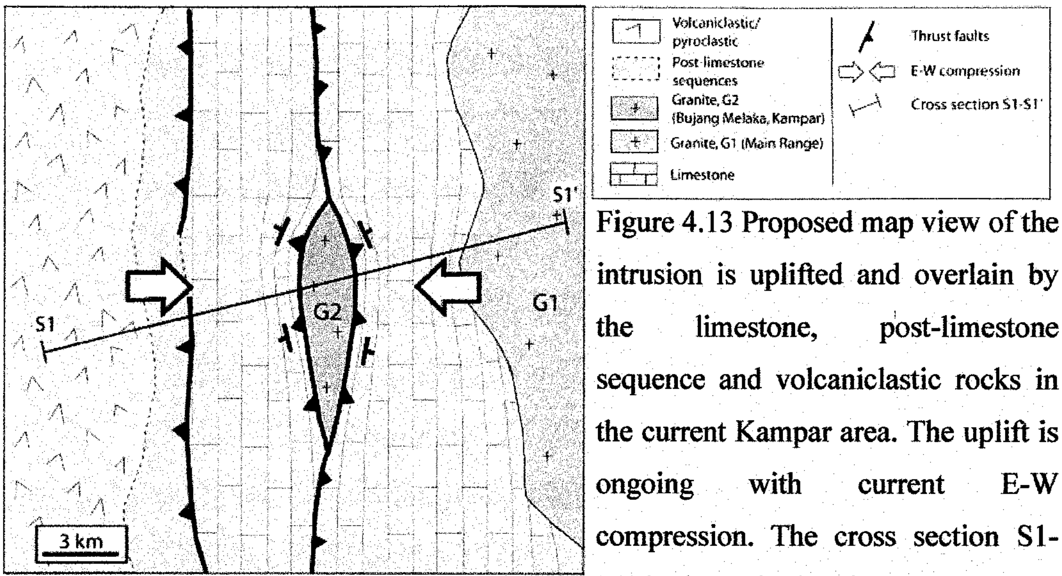


Figure 4.13 Proposed map view of the intrusion is uplifted and overlain by the limestone, post-limestone sequence and volcaniclastic rocks in the current Kampar area. The uplift is ongoing with current E-W compression. The cross section S1-S1' is shown in the Figure 4.14.

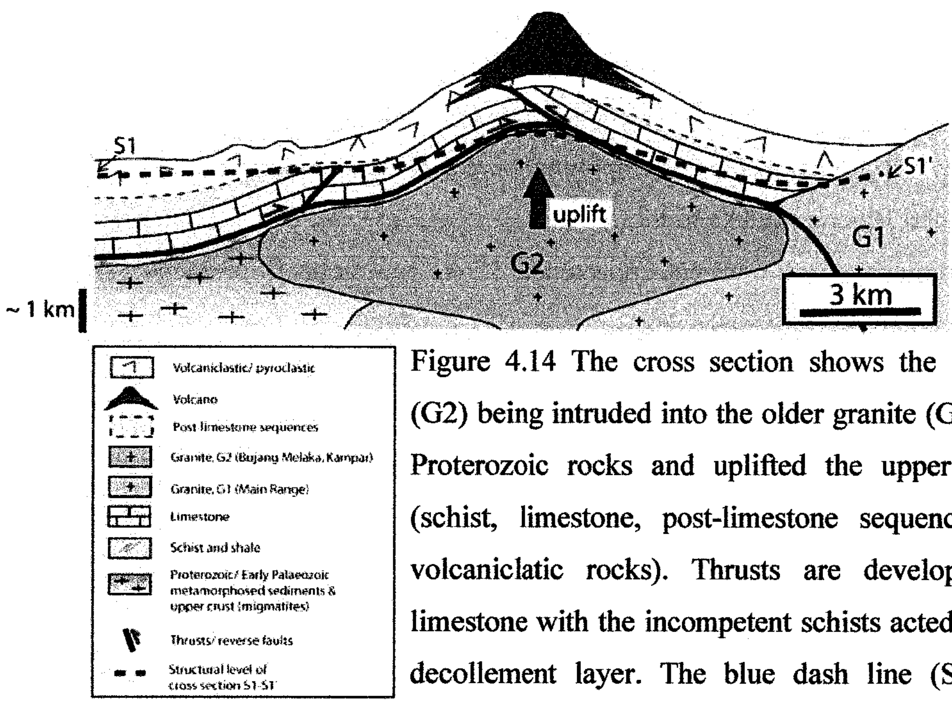
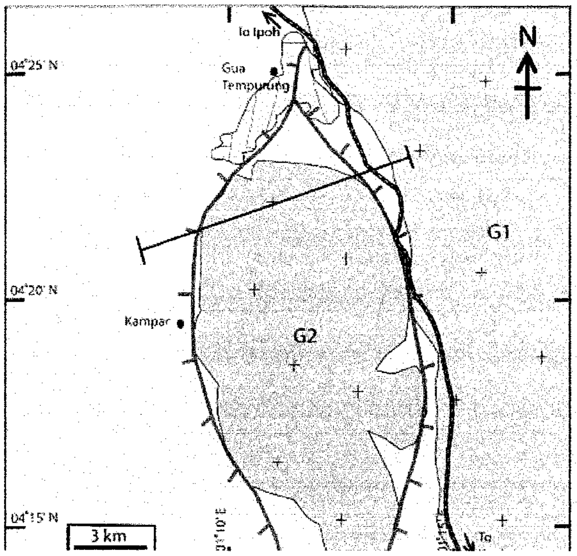


Figure 4.14 The cross section shows the granite (G2) being intruded into the older granite (G1) and Proterozoic rocks and uplifted the upper rocks (schist, limestone, post-limestone sequence and volcaniclatic rocks). Thrusts are developed in limestone with the incompetent schists acted as the decollement layer. The blue dash line (S1-S1') represented the subsequent erosional surface.



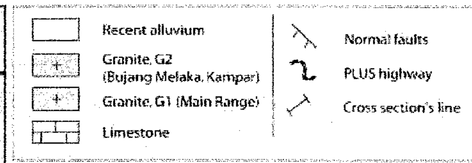
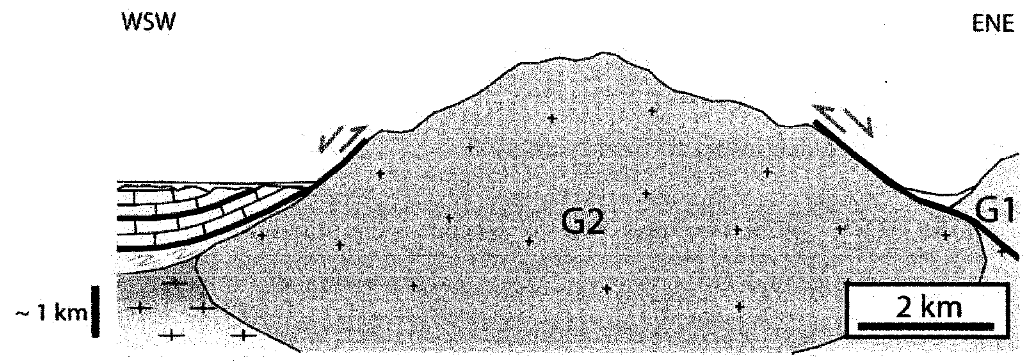


Figure 4.15 Map showing the granite intrusions (G2 and G1) and the remnant limestone hill in the southern part of the Kinta Valley. Thrust faults have transformed to normal faults due to the uplift of the G2. A cross section is made from the WSW to ENE and shown in the Figure 4.16.



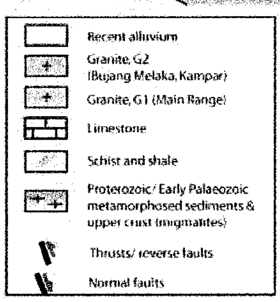


Figure 4.16 Cross section showing that the post-limestone sequences on top of the granite (G2) having been totally eroded. Limestone and the rocks underneath are covered by the recent sediments. Thrust faults appear to have been reworked as normal faults.

4.1.3 Drainage Anomalies

Kinta Valley was bounded by Mesozoic Granite at the east and west. Middle of the valley was mostly covered by recent sediments. Lithology that can be observed on the surface is those that in topography high or high relief, such as limestone. The meteoric water flowed from the highland (granite) to the lowland (middle of the valley), was transported and deposit sediments within river or stream, and formed the alluvium plain which dominant within the valley. The drainage was developed when the surface water flows through. The development of the drainage depends on the characteristics of the bedrock such as lithology, fracture set, slope gradient, and more. The information of the bedrock which is covered by sediments, could be identified through drainage study like drainage anomalies. It provides more evidences to argue the results obtained from surface outcrop. The drainage anomalies were traced out and showed in Figure 4.17.

Southern zone

Southern zone referred to southern Kinta Valley which included Batu Gajah, Tanjung Tualang, Malim Nawar, Gopeng, and Kampar areas. This zone is composed of several sets of parallel drainage anomalies, which are ENE-WSW, NNE-SSW, and NNW-SSE and named according to their azimuths.

ENE-WSW anomalies have been observed in the alluvium between Batu Gajah-Tanjung Tualang and Gopeng (Figure 4.18). The anomalies commonly have around 3km long. The spacing between anomalies is quite regular. When getting closer to Main Range like Gopeng and Gunung Tempurung areas, the dominant anomalies change to NNE-SSW direction. NNE-SSW anomalies are closely spaced and relatively shorter compared to the previous anomaly set (ENE-WSW). The anomalies can be extended to north and connected to the N-S striking fractures in the granite which commonly found in Lubuk Timah, Gunung Datok and Tambun areas. These anomalies are likely to be regional normal faults which normally formed in curved-shape. The orientation of the structures (normal faults) can be deduced E-W to NW-SE extension.

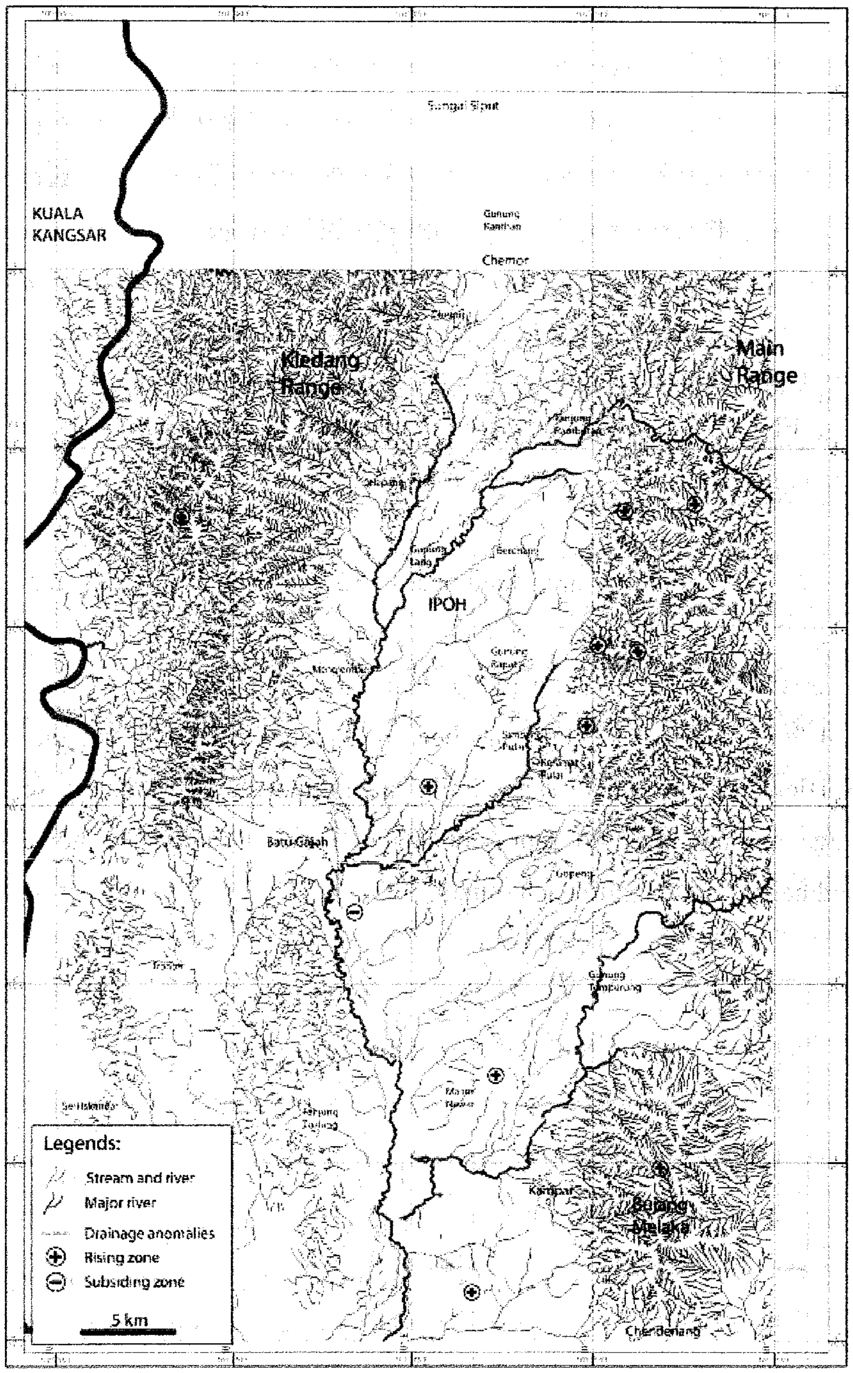


Figure 4.17 Drainage anomalies of the Kinta Valley.

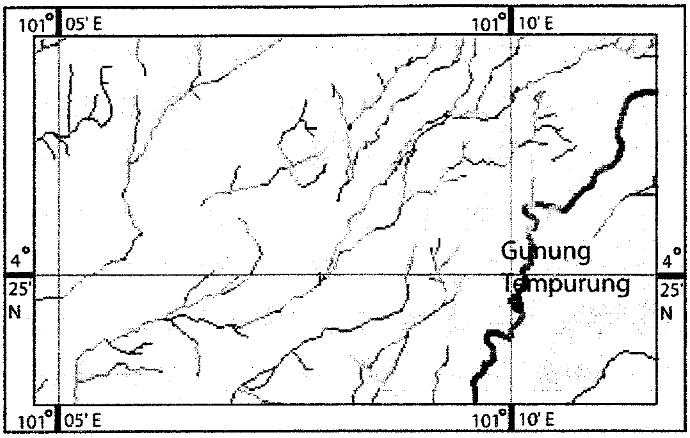


Figure 4.18 Drainage anomalies in the west of Gunung Tempurung, southern Kinta Valley. ENE-WSW anomalies are dominant at Southwestern part, and gradually changed into NNE-SSW anomalies at northern part.

NNW-SSE anomalies are found near to Sg. Kinta next to Batu Gajah and Tanjung Tualang (Figure 4.19). It is very closely spaced and localized. The major anomaly is the one which located on top of Sg. Kinta and included most of the river body. A normal fault near to Sg. Kinta, has been interpreted in DEM based on the change of the surficial texture, and it has similar azimuth with this anomaly set. Hence, the drainage anomalies could represent several normal faults like horse tails, which formed nearby and next to each others.

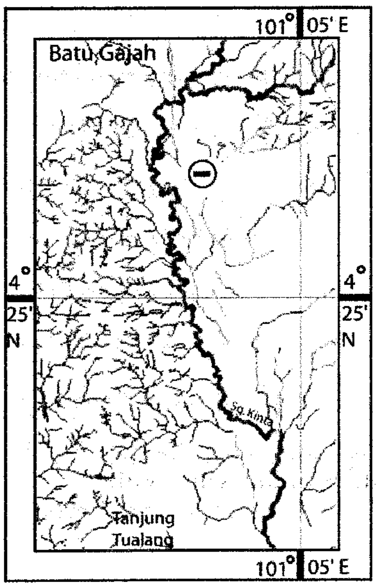


Figure 4.19 NNW-SSE drainage anomalies found near Batu Gajah-Tanjung Tualang and next to Sg. Kinta. A subsiding area (with the minus sign) has been interpreted at the intersection of the NNW-SSE and NE-SW anomalies.

Radial – centrifugal drainage anomalies stand out remarkably in Bujang Melaka and Malim Nawar (Figure 4.20). The centrifugal anomalies have been marked by '+' correspond to the rising zone. Bujang Melaka's drainage anomalies are located on a round intrusion, which all the rivers flowed out from the peak of hill. The anomalies of Malim Nawar have a roughly triangle-shaped and elongated in NE-SW direction. The anomalies were caused by the dome structure under the surface. The dome is probably the schist anticline just like the large fold found in Batu Gajah Schists.

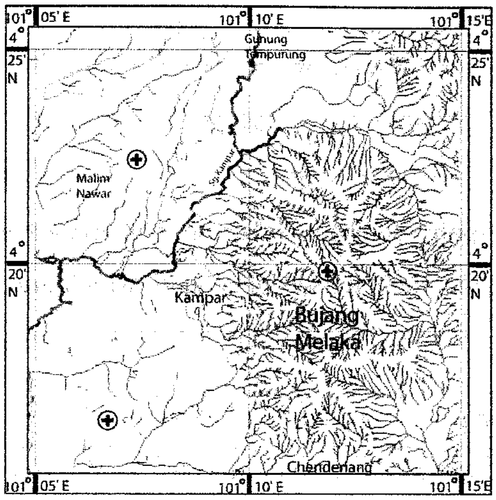


Figure 4.20 Radial drainage pattern has been discovered in the Malim Nawar and Bujang Melaka. A dome is estimated to be formed underneath Malim Nawar, which is now fully covered by Quaternary sediments. Bujang Melaka is a dome-shaped pluton, therefore rivers flowed out to all directions from peak.

A subsiding zone has been discovered in the south of the intersection of the Sg. Kinta and Sg. Raia and labeled with a '-' symbol. The drainages are found disappeared here and may be connected to groundwater system. It may be underline the existence of pull-apart basin which associated with the faults nearby.

Relatively shorter anomalies were located between Batu Gajah and Simpang Pulai with azimuth ranges from NW-SE to N-S (Figure 4.21). It occurred in minority. The anomalies are found in the schist province and formed in between lithologic ridges. The anomalies are the depressions which represented the strata plane. The gradually change of the azimuth of the anomalies could be due to the folding.

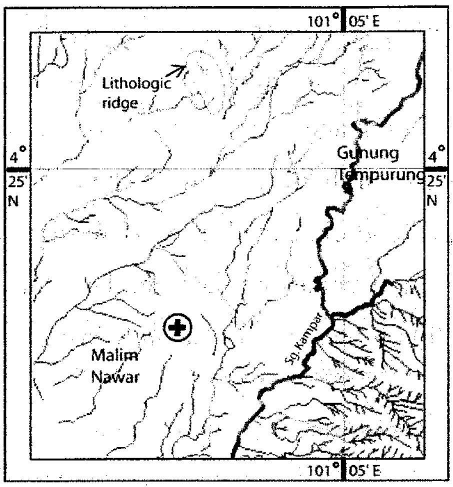


Figure 4.21 Drainage anomalies found at west of Gunung Tempurung, with range from NW-SE to N-S. The anomalies probably represent the depression zone between lithologic ridges.

Northern zone

Northern zone includes the area around Ipoh, Bercham, Jelapang, Chepor, Chemor and Tanjung Rambutan. Two major drainage anomaly sets are found, which are NE-SW and N-S.

NE-SW anomalies are relatively longer compared to the others. It is quite regularly spaced. The anomalies can be observed on the major rivers (Sg. Pari and Sg. Kinta) in western Kinta Valley (Figure 4.22), but it totally absent in granite at east. The average length of the anomalies (~5km) suggested that they are faults. The faults are likely to be result from a late deformation, because it crosscuts other fractures. The anomalies are able to extend and connect to NNW-SSE set in Batu Gajah at southern zone, and become large normal fault. The curved- and sigmoid-shaped of the normal faults in Kinta Valley, can be caused by right-lateral strike-slip faults, which almost parallel the granite contact (Figure 4.24). The strike slip faults generated diffuse pull-apart basins by forming multiple normal faults.

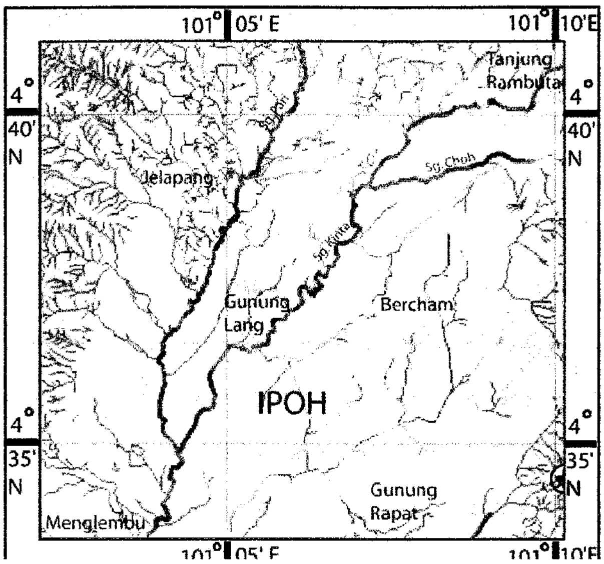


Figure 4.22 NE-SW drainage anomalies can be observed around Ipoh. The anomalies are likely to be faults due to their length.

N-S set is actually composed of anomalies range from NNW-SSE to NNE-SSW. The anomalies have been observed in both granite and alluvium in the valley (Figure 4.23). The anomalies are interpreted as tension faults formed at the tip of gentle fold which initiated by the E-W compression.

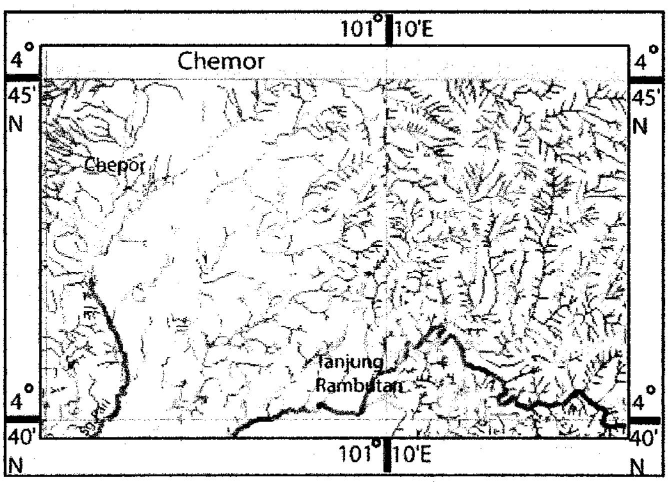


Figure 4.23 N-S drainage anomalies have been found in the northern part of the valley. They are closely packed and formed in alluvium (sparse drainage area) and granite (dense dendritic drainage area at east).

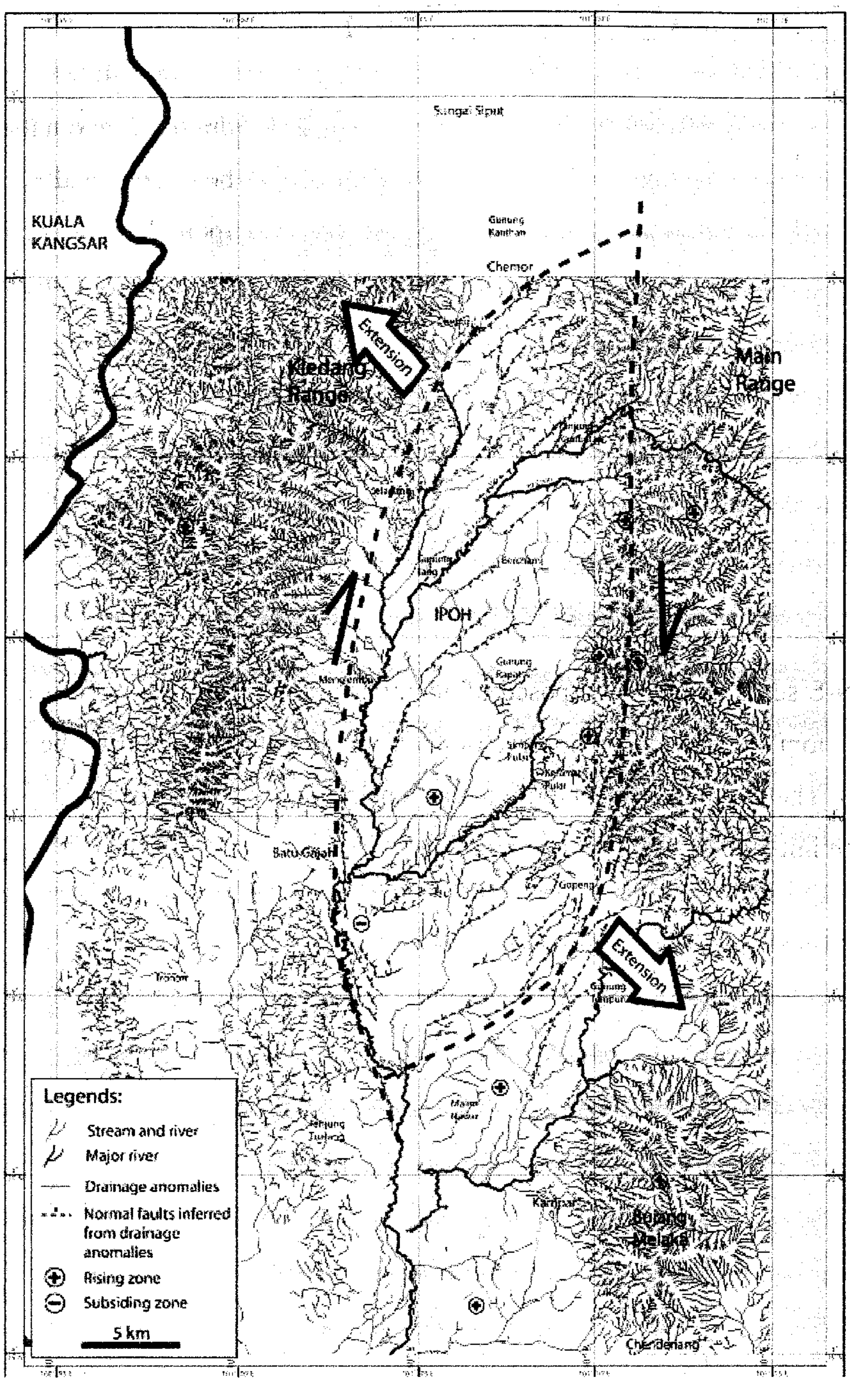


Figure 4.24 Proposed structural setting of the Kinta Valley based on drainage anomalies. Parts of the anomalies are interpreted as normal faults which fitted into a regional pull-apart basin initiated by right-lateral fault.

4.2 Measurements in the Limestone

4.2.1 Bercham

The outcrop in Bercham is located in Gunung Ginting. It is relatively away (~4 km) from the granite. The beddings are gently dipping and are composed by the light grey-coloured, highly fractured and highly crystallized limestone; and thinly, dark grey-coloured, incompetent clayish limestone. Most of the outcrops are fresh, well exposed, and it contains well-preserved tectonic indicators such as slickensides, Riedel fractures, C-S bands and normal faults. These tectonic indicators developed under thrusting and strike-slip faulting which induced by a compression with rough E-W direction.

Thrust faults

Several discontinuities have been observed and these discontinuities are parallel to the bedding planes. These structures are interpreted as the thrust faults. It propagated along the bedding plane as indicated by striations on the strata surface (Figure 4.25). The transport direction is E-W but the senses of motion of the unconformities or thrusts are usually not well defined. The thrusts may be top to the East or top to the West depending on location.

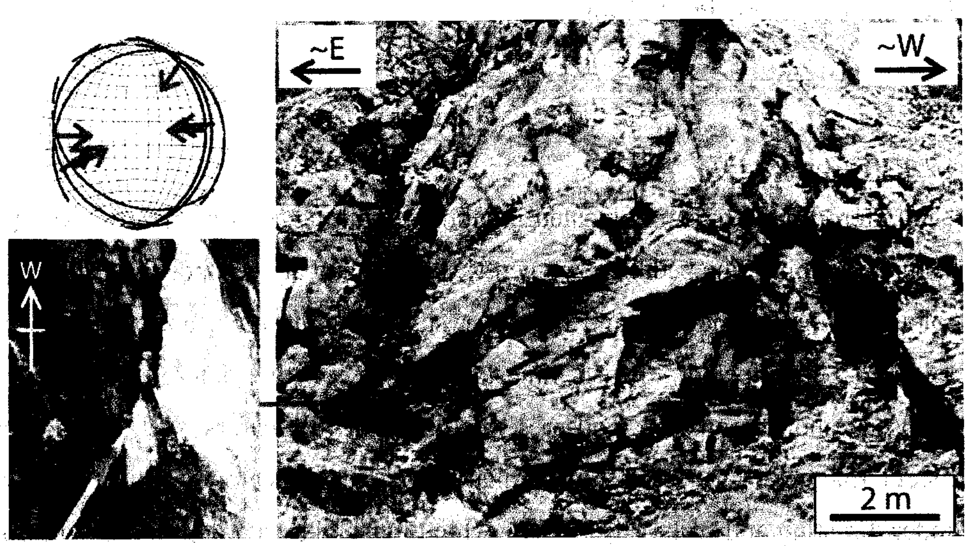


Figure 4.25 Thrust faults in the limestone of Bercham. The small insert shows well-preserved slickensides on the bedding planes and underlines D3 reverse slipping surfaces. The red arrows show the direction of the movement of the blocks, solid arrow for the confirmed movement, dash arrows represents the inferred movement.

Strike-slip faults

The cliffs of the limestone hill are almost vertical, and the calcite cements and striations are usually can be observed on the surfaces, and thus confirm that they are fault planes. The cements on the slickensides of the faults, are formed by the relative movement of two fault blocks. The low angle pitches have indicated the faults are in strike-slip (Figure 4.26) which composed both right- and left-lateral movement. These faults are highly dipping and formed in conjugate set, right-lateral faults striking in NE-SW and left-lateral faults striking in E-W. The orientation of the conjugate faults are induced an ENE-WSW compression. The cliffs of the limestone hill of Bercham could be represented by the conjugate strike-slip faults, shown in the satellite image. A similar conjugate fracture set is found at the limestone hill to the south of the Bercham, which is probably the same fracture set as that of Bercham (Figure 4.26). The strike-slip faults predated the thrust faults based on their cross-cutting relationship (Figure 4.27).

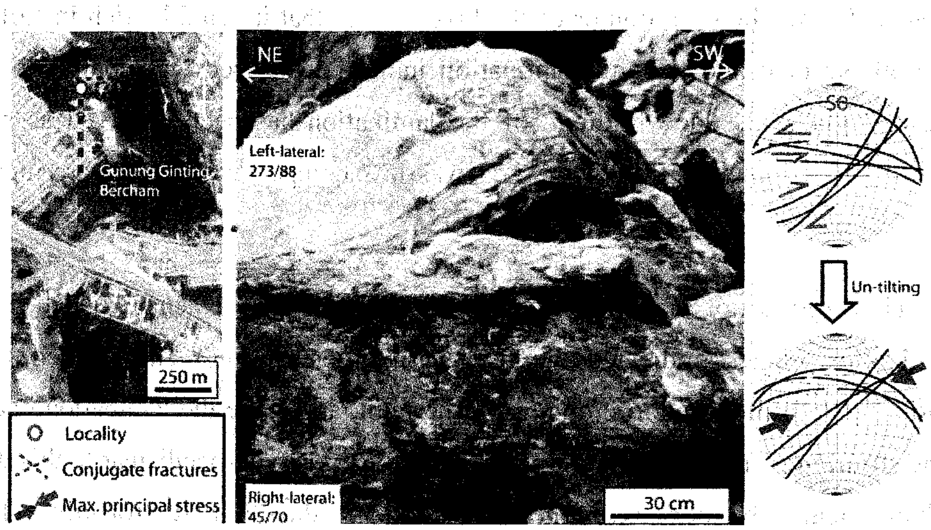


Figure 4.26 Conjugate strike-slip faults formed in the limestone of the Bercham. We clearly recognized slickenside, and deduce a ENE-WSW compression. A similar orientation of conjugate fracture was observed at the limestone hill to the south of Bercham, thus this fracture set was inferred as D2 fractures too. S0 in stereonet is bedding.

Figure 4.27 Vertical strike-slip fault formed at the cliff face. It has been cut and displaced by gently dipping reverse fault/thrust fault.

Fold in the thin black-coloured muddy bed

The thin dark grey-coloured bed which shows a clayish appearance can be found in the major discontinuity or bedding plane (Figure 4.28). The thickness of this bed is between 3cm to 10cm, which the thickness of the laminations inside the bed ranging from 2-5mm. The dark colour of the layer shows that it could be rich in carbon. The smooth surface and the thin lamination indicated this bed was composed by fine-grained material. The "folding" of the lamination has been observed as shown in Figure 4.28, which indicated the bed was less competent and therefore more easily deformed.

This fold is not a slump, because the striations and cements existed in between lamination planes, indicated the bedding-parallel slipping. The "folded" structure could be deformed due to dragging of the fault, and make the lamination overturned. The striation is in NE-SW trending, and the fold axis is perpendicular to this direction, which means the compression was in NE-SW direction. It probably acts as the décollement layer for the fault.

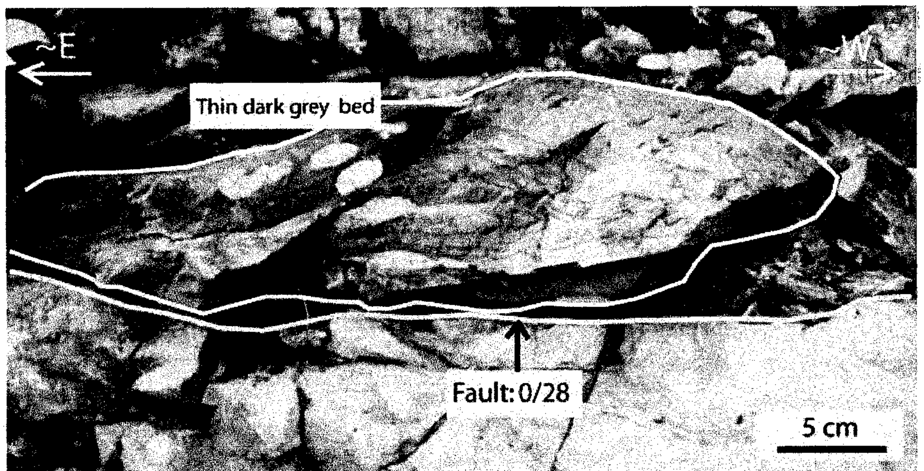


Figure 4.28 Dark grey-coloured thin bed formed on a fault plane in Bercham. The fold structure within the bed was related to fault, based on the striation cement found on the laminations of the layer.

After examined the cross section of this thin bed (Figure 4.29), the fold structure was created by numerous faulting along the lamination plane. The features show in the cross section of the thin bed likely to be a C-S band, which cleavages are parallel to the lamination plane and shears are the normal faults. The occurrence of the C-S band is also indicated the rock has been deformed in ductile manner.

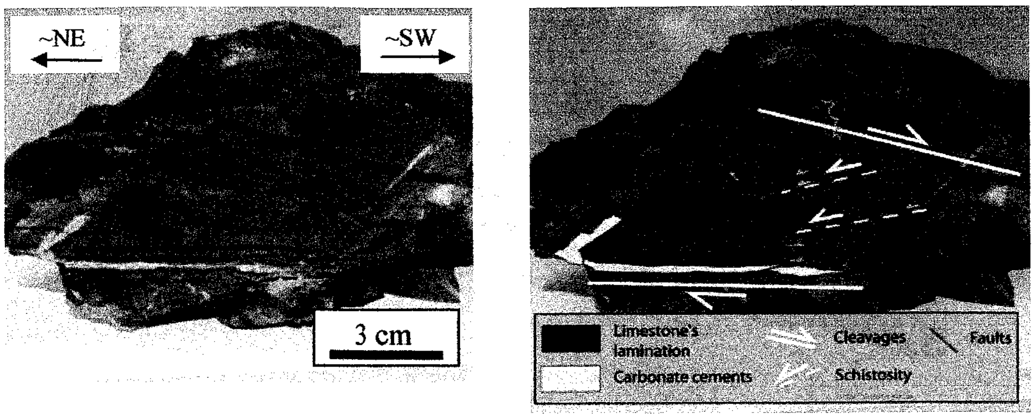


Figure 4.29 Cross section of the thin dark grey-coloured bed, original on left and interpreted on right. Numerous faults (red lines) were formed in this thin bed, most of the time the faults propagated along the lamination plane. Those faults are oriented like C-S band, which cleavage parallel to the laminations and shear plane represented by the faults (white dash lines) that appears inclined relative to the lamination.

Cleavage-schistosity band (C-S band)

A thin, black, shaly layer is believed to be sitting in the fault zone, sandwiched by light grey thicker limestone beds. The shaly layer behaves ductile and easily deformed. Two discontinuities were formed within this layer, marked by the white dash lines (Figure 4.30). The discontinuities cut the thin layers into uneven thickness with slightly boudinage-look. It probably caused by the dragging of the fault. The shaly layer contains dense, nearly parallel fractures, could be schistosity/cleavage (yellow dash lines), common formed in the shear zone. The combination of the shearing discontinuities and schistosity/cleavage can be considered as C-S band. This structure also found in the hand specimen (Figure 4.29).

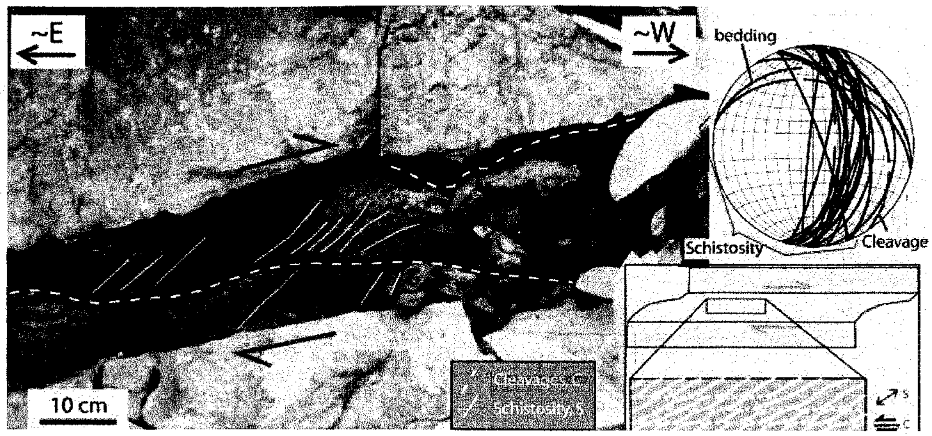


Figure 4.30 Schistosity or cleavage (yellow lines) formed the C-S band in the thinly black-coloured bed. Shears were marked by the white dash lines. C-S band underlines a reverse fault based on the orientation of the schistosity in the thinly black-coloured incompetent layer. The movement of the fault is marked by the red half arrow.

Riedel fractures

The reverse fault was identified by recognition of the Riedel fractures (Figure 4.31). The limestone of Bercham were crystallized and behave as a competent unit, likely the brittle deformation has induced the formation of the Riedel fractures. Those fractures were obliquely oriented to the discontinuity/fault and parallel to maximum principal stress direction. The fractures were striking NW-SE, similar to the correspond fault.

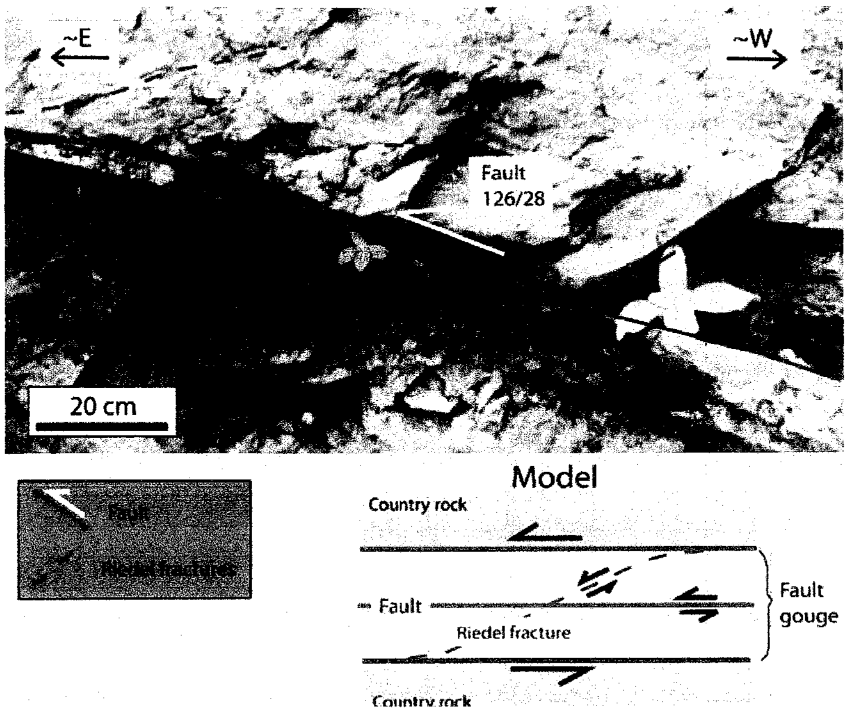


Figure 4.31 Minor curved fractures developed around the major gentle fracture. The red dash lines marked the location of the curved fractures, or Riedel fractures which indicate brittle deformation of a reverse fault to the east (direction of faulting marked by white half arrow). They are located around a fault/discontinuity. The small insert at the bottom is the model illustrates the orientation and motion of the fault plane and Riedel fracture.

Normal faults

Conjugate fracture set is clearly seen on the outcrops. Those fractures are highly dipping (~60°) and striking N-S (Figure 4.32). The fracture planes are steep, suggested it is normal faults. They commonly cross-cut the whole outcrop as well as other fracture sets, showing that it is a late deformation.

Figure 4.32 Conjugate normal faults observed on one outcrop in Bercham. The faults strike in N-S and highly dipping.

4.2.2 North of Gunung Datok (Tambun)

4.2.2.1 Banjaran

Banjaran stated here is referred to Banjaran Hotsprings Retreat, situated in the Northern part of the Gunung Datok, Tambun. It is also the well-known hot springs in Kinta Valley. The limestone is nearly vertical dipping, striking in N-S direction, highly fractured and varying colours from black to light grey, occasionally white colour. Whole limestone has been re-crystallized due to the metamorphism.

The major fracture set is conjugate fractures. The fracture set strike in N-S direction and dipping in ~60°. Both outcrops and also hand specimens (Figure 4.33, 4.34) show this fracture set. These fractures have been un-tilted, and appear to be a highly dipping conjugate set which indicate a former E-W compression.

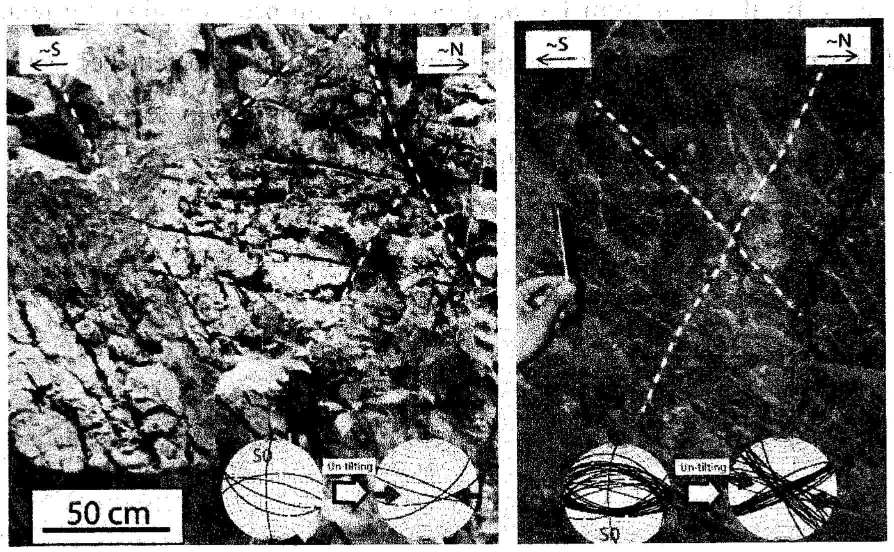


Figure 4.33 Conjugate fractures observed on a vertical limestone bed. Line with S0 on stereonet represents bedding; black lines are conjugate fractures; pink-coloured arrows pairs represent the maximum principal stress direction (σ_1). Pen as scale, it is ~ 15 cm long.

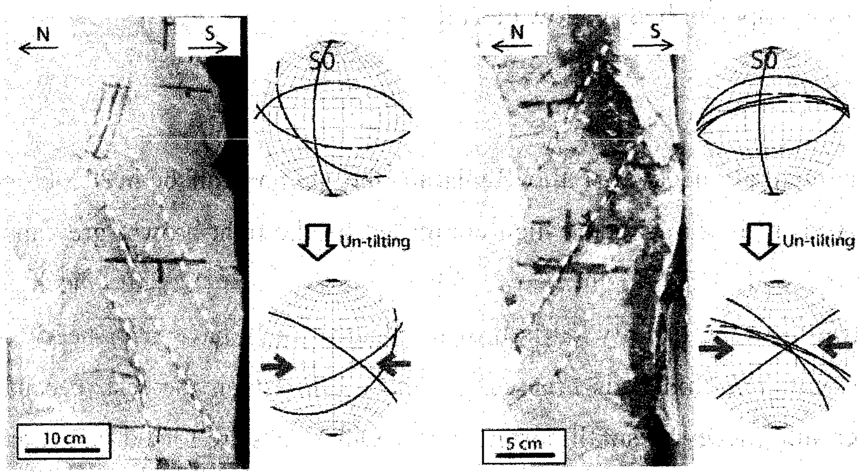


Figure 4.34 Conjugate fracture set (yellow dash lines) formed on two oriented hand specimens. Note the similarity to the D2 fracture set at the outcrop-scale in Figure 4.33. In stereonet, line with S0 is bedding, other black lines are fractures, pink-coloured arrows represented the maximum principal stress direction.

The conjugate fracture set found in the 'balcony' of the Banjaran (Figure 4.35). The fractures were developed in two beds which behave competent and incompetent respectively. It began from the hard or competent bed in a high dip relative to the bedding plane, and propagated to the next soft or incompetent bed with lower dip angle. The development of the fractures is just limited to several beds, so it was interpreted as the early fractures that formed before tilting.

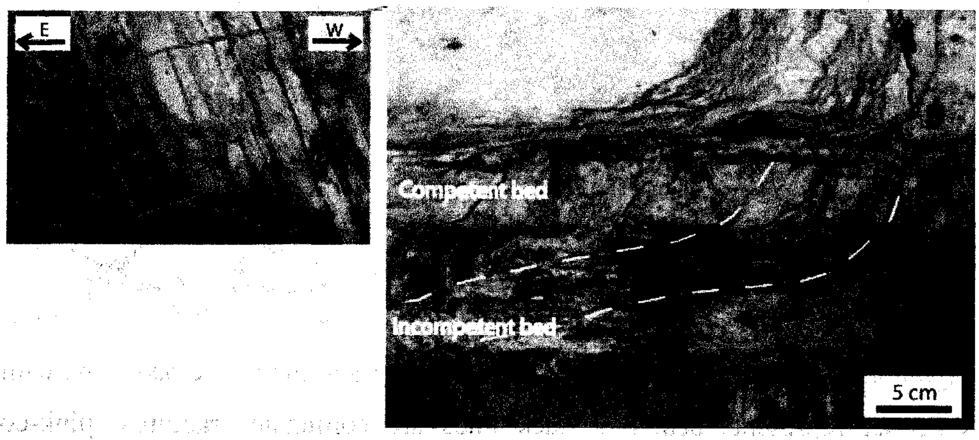


Figure 4.35 Varying fault dip angle with lithology in the limestone cave of Banjaran Hotspring. Fractures initiated from the competent bed at top and propagated to the lower incompetent bed (yellow dash lines).

In meditation cave of the Banjaran, the slumps can be well observed. It was observed in the limestone which composed by the light-brown, grey and dark grey-coloured beds with thickness of ~50cm (Figure 4.36). Besides the limestone beds mentioned above, thinly dark brown-coloured beds have also been found in the limestone. The thin beds are seen as more brittle than the rest, because it usually broken into pieces by small normal faults. Other beds are folded tightly and deformed in ductile manner with simple shear movement. It could be caused by the limestone having been heated and partially melted by the nearby granite intrusion (<100m). A folded (deformed) vein has been observed in the same cave (Figure 4.37) which could be a tension fault before, and later affected by ductile deformation.

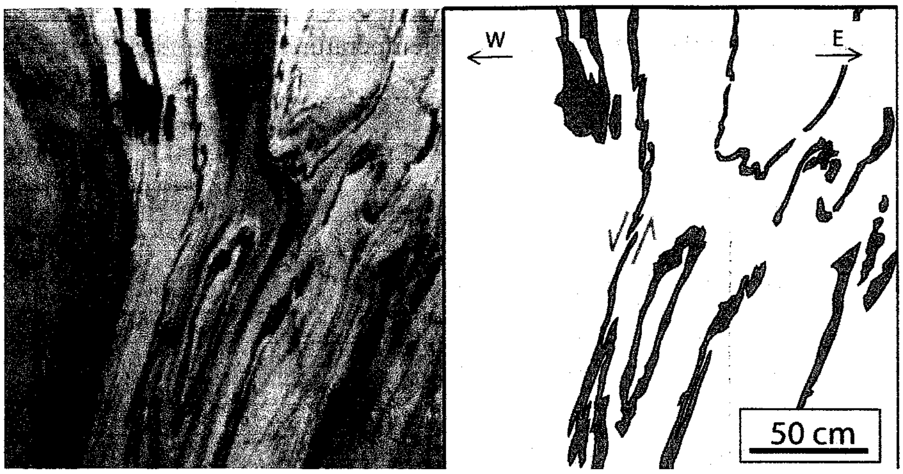


Figure 4.36 Slumps structures observed in the Meditation cave in Banjaran. The small normal fault in the simple shear motion can be easily found on the brown-coloured thin beds, which are commonly acted as the boundary of the slumps. These beds are apparently more competent or brittle compared to the black- and light-coloured beds.

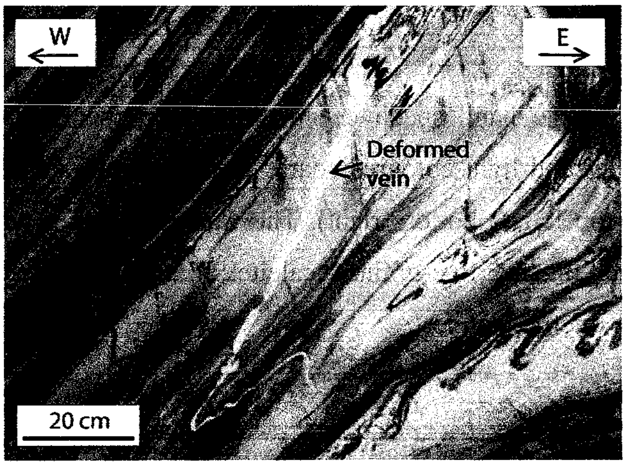


Figure 4.37 A vein, probably former tension fault, has been found in the ductile limestone bed. The vein has been folded (deformed), probably by the ductile deformation, which indicates a brittle deformation event (tension fault) was occurred before ductile deformation (small normal faults).

The thin section of the hand specimen collected from Banjaran, Tambun, is highly crystallized (Figure 4.38) just like the observation of the outcrop in the site. The calcite crystals have various sizes with their own zonations. The size of the fine-grained calcite is few tens of micro-meter; while the coarse-grained calcite can reached few hundred micro-meter. The fine-grained calcite obviously formed laminations which sometimes curved, and could indicate the limestone has been deformed in ductile manner at high temperature due to the nearby hot granite intrusion.

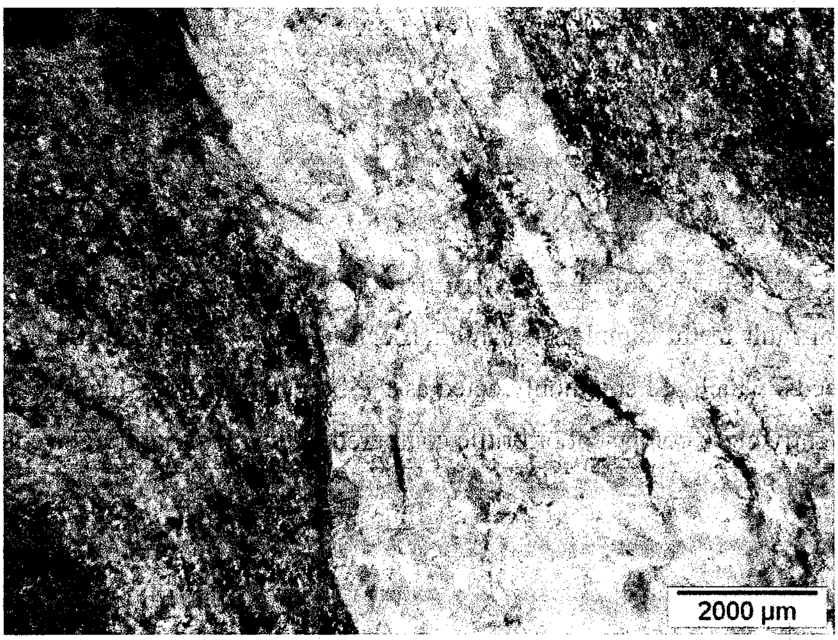


Figure 4.38 Photomicrograph of the hand specimen collected from the Banjaran, Tambun. The dark-coloured fine- and light-coloured coarse-grained calcite generally aligned in the same direction (top left to bottom right). The wavy lamination of the calcite can be clearly observed in the fine-grained calcite. It indicated that the limestone has been deformed in ductile manner.

4.2.2.2 Lost World of Tambun

Lost World of Tambun is a theme park located at the eastern side of the valley, 1km to the south of the Banjaran. The characteristics of the limestone are similar as Banjaran: highly crystallized, fractured and highly dipping.

Conjugate fractures are the major fractures formed in the limestone in outcrop and hand specimen (Figure 4.39). The fractures seem like extension normal faults with the high dipping and striking in WNW-ESE direction. After unfolding, those fractures are striking in ~E-W and NW-SE and vertical dipping, which induced an ESE-WNW compression. It is similar to the conjugate fracture set found in Banjaran.

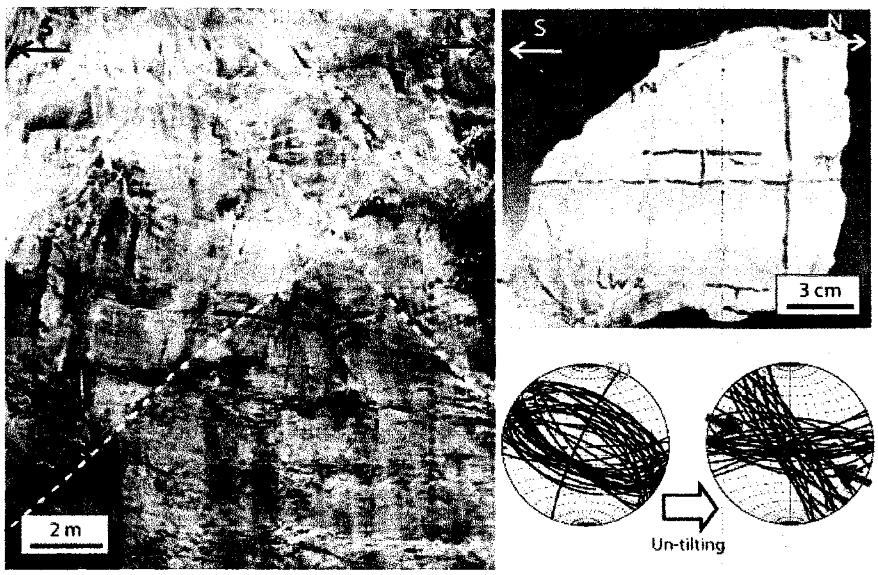


Figure 4.39 Conjugate fractures (marked by yellow dotted lines) found in both outcrop and hand specimen of the limestone in the Lost World of Tambun. The hand specimen was collected from the location where the red dash arrow pointed. The fracture set shows a rough ESE-WNW compression after tilting restoration. S0 is bedding.

The step-like fractures have also been observed in the limestone (Figure 4.40) which offset the cliff face. It has a very low dipping angle and strikes in ~ N-S direction. Surprisingly, the fractures formed a high dip, ~N-S striking fractures after un-tilting. It can be interpreted as an early extension event which induced the fractures when the beddings are still horizontal.

The major fractures or discontinuities have been observed on the cliff face of the limestone hill (Figure 4.41). It cut the hill from top to bottom in a low dip angle, and the intense dissolution has marked these fractures even obvious. No well preserved slickensides have been found, and it has probably been erased by the dissolution. The fractures have been first observed in the satellite image with triangular pieces appearance, and interpreted as thrust faults. So, it was considered as thrust fault and propagated to the east towards the granite.

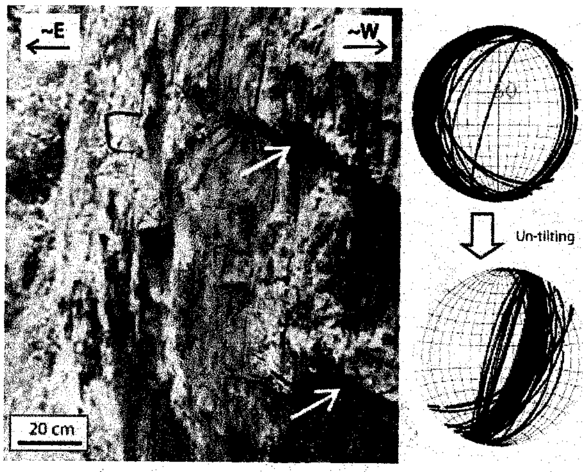


Figure 4.40 The fracture set found in the outcrop which located opposite to the 'Needle of the Tambun'. The offset or step-like structures created by the fractures can be observed (white arrows). The fractures (black lines) show the ~N-S striking after unfolding. S0 represented bedding of the limestone.

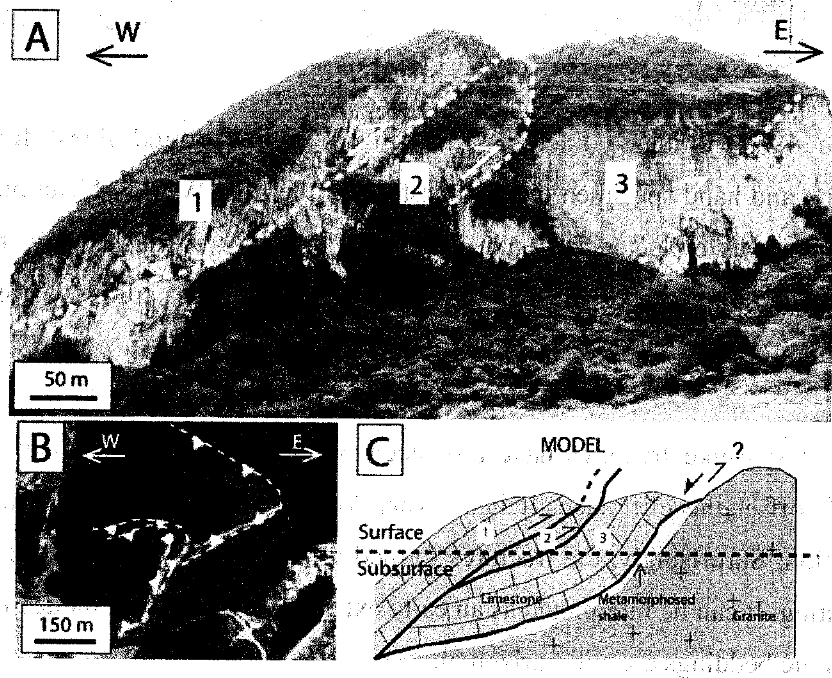


Figure 4.41 [A] Imbricate thrust faults in Tambun marked by yellow dash lines in the limestone outcrop, [B] Satellite image shows the triangular pieces representing thrust imbrications, and [C] Model that illustrates the possible orientation of the thrust faults on surface and subsurface. The thrust faults could have initiated and propagated in sequence from 1 to 3.

4.2.3 South of Gunung Datok

Southern part of the Gunung Datok, is generally surrounded by the residential area. Other buildings such as Buddist Temple, Polo Club, fish farm, plantation areas are located at the foothill of Gunung Datok. The limestone hill has been cut by major fractures and formed valleys. It is located next to the granite intrusion, but the granite contact remains unclear in the field, since it is covered by thick vegetation and Quaternary sediments. The limestone is crystallized, varying in strike and dip and highly fractured (Figure 4.42).

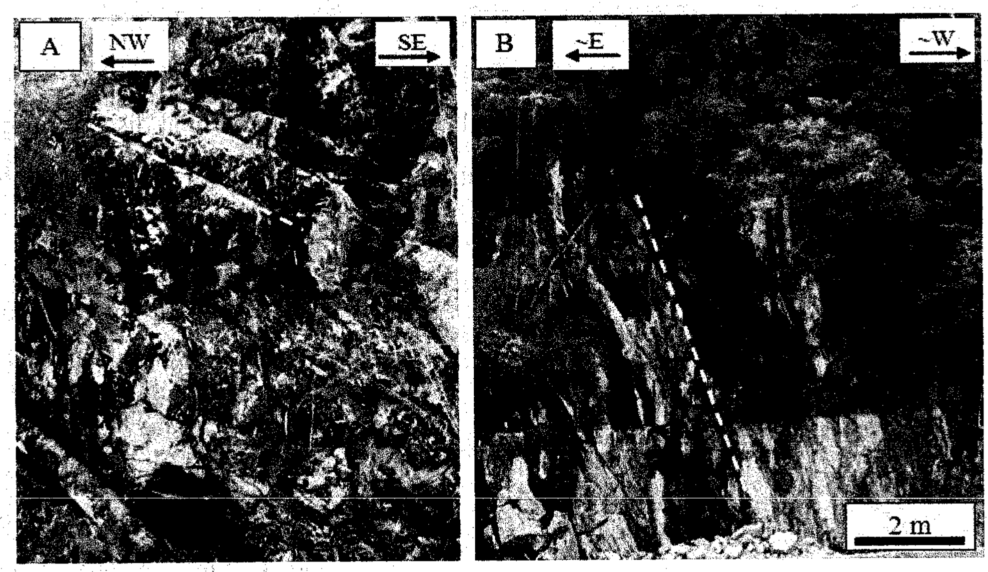


Figure 4.42 Both outcrops are located near the temple, in the NW-SE valley in the Gunung Datok, showing different dipping (yellow dash lines). [A] Gentle dipping limestone. Bag as scale, width is ~30cm. [B] High dipping limestone.

4.2.4 Gunung Lang

The study is mainly focused on the northern part of the Gunung Lang, due to the accessibility and the well exposed outcrops. The northern part of the Gunung Lang was a quarry before and is now operating as a recreational park. The limestone is all crystallized and displayed white-grey bands as bedding. The bedding is almost vertical and striking in a N-S direction (Figure 4.43, 4.44).

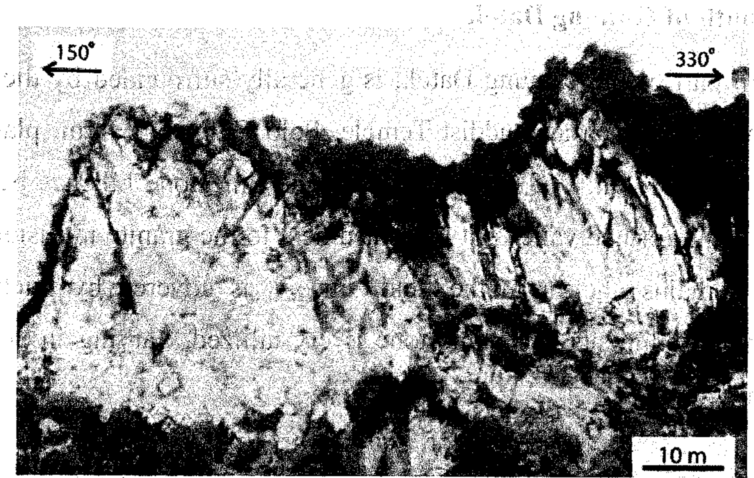


Figure 4.43 One of the limestone hills in the Gunung Lang. Highly fractured limestone has covered the real bedding plane, those nearly vertical discontinuities are mostly likely the bedding. The discontinuities at the NW side of the hill seem to turn implying they could be part of the fold.

Figure 4.44 Highly crystallized limestone composed of thinly, interbedded light and dark bands which represented the bedding. The limestone is almost vertical and striking in N-S direction. Compass as scale, the width of compass is 6.5cm.

4.2.5 Gunung Rapat

Gunung Rapat is the biggest limestone hill in the Kinta Valley. It situated in the middle of the valley and south of Ipoh (Figure 4.45). The limestone is crystallized, fractured and no original fabrics are found. The limestone beds are showing gentle attitude at the western part of the hill, to high dipping at the eastern part. The hill was cut by few valleys trend NE-SW to NNE-SSW directions, represented the major factures which probably originated from regional tectonic activity.

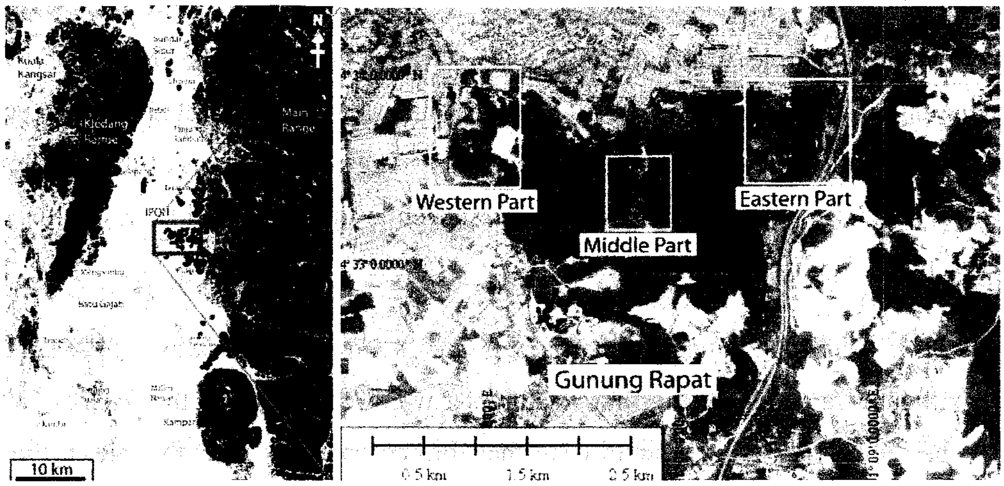


Figure 4.45 The locations of three parts (Western, Middle and Eastern Parts) of the Gunung Rapat.

4.2.5.1 Western Part

The outcrops are near to the Chinese temple and Petronas petrol station. The limestone bedding is usually difficult to determine because of intense concretion and numerous fractures. Through the detailed observations, the limestone has been confirmed to be dipping gently (Figure 4.46).

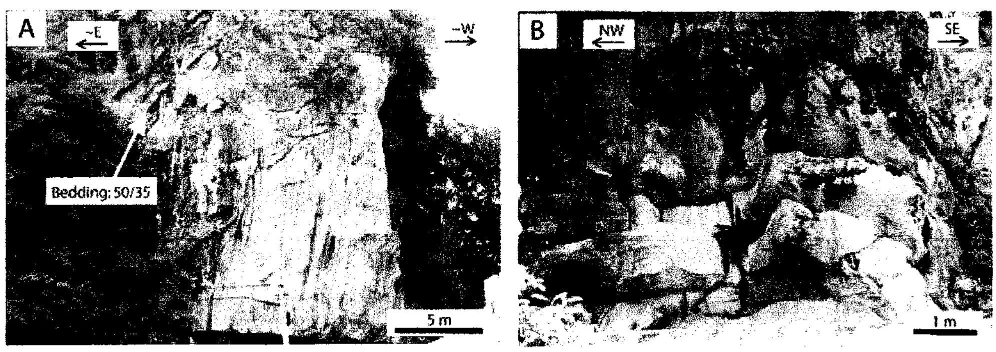


Figure 4.46 [A] Limestone beds at the top part of the outcrop are relatively clear and showing its gentle dipping. [B] Gentle dipping limestone beds found in the Chinese temple, Western part of the Gunung Rapat.

4.2.5.2 Middle Part

A Chinese temple was built in the cave which located in the middle part of the Gunung Rapat, named Kek Lok Tong. The field observation is relatively concentrated in this locality due to the large good exposure. The characteristics of the limestone are generally same as the other localities: gentle dipping, highly crystallized and fractured.

Two sets of conjugate fracture sets are found in this locality. NW-SE striking conjugate fractures are the first fracture set which found beside the 'Eye of Kek Lok Tong' (Figure 4.47), the small cave that formed on the peak of the one of the tower karst. The conjugate fractures are likely contributed to the formation of the cave, or even ~N-S trending major valleys in the middle of the Gunung Rapat. The second fracture set is observed in the foothill, which are E-W striking conjugate normal faults (Figure 4.48). The dragging of the bedding near the fractures is the indicator that the displacement has occurred along the fracture.

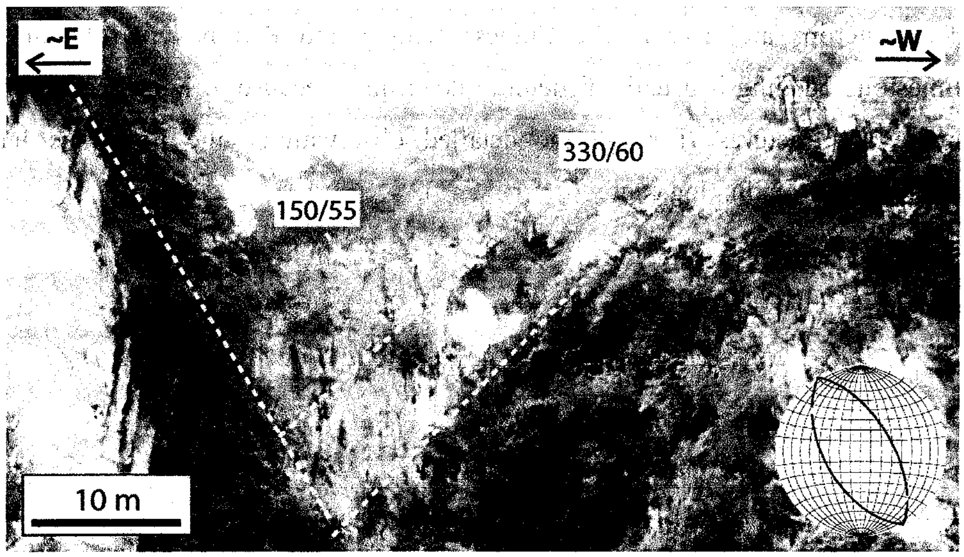


Figure 4.47 'Eye of Kek Lok Tong', the cave located on top of tower karst in Kek Lok Tong (Chinese temple). It probably formed by collapse of rocks with conjugate fractures (yellow dash lines).

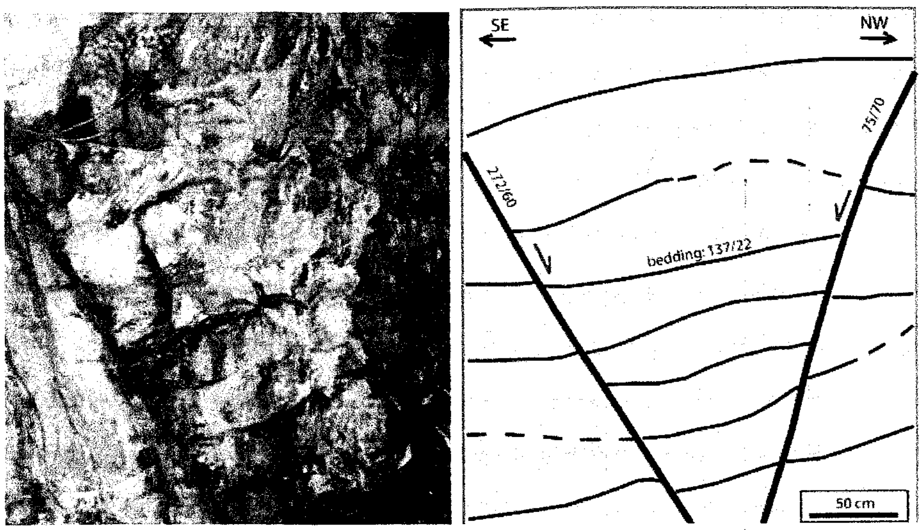


Figure 4.48 Conjugate fractures found in the gentle dipping limestone near the entrance of the Kek Lok Tong. Based on the dragging feature of the bedding near fractures, the conjugate fractures are considered as normal faults which induced N-S extension.

4.2.5.3 Eastern Part

Eastern part of the Gunung Rapat is mainly covered by the plantation area and it is next to the PLUS Highway. The limestone is generally light grey in colour with some dark colored bands (Figure 4.49). Those bands are the only indication of the bedding. The bands are usually too pale and caused the beddings to be hard to identify. The bands are highly dipping and striking in N-S. No significant and consistent fracture set has been found in this locality.

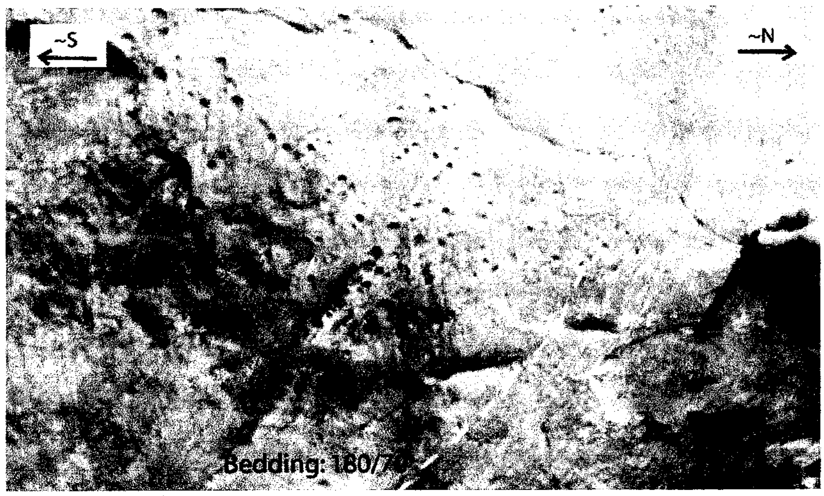


Figure 4.49 Limestone of the Eastern part of the Gunung Rapat. It is highly crystallized, and bedding (yellow dash line) is affected by the re-crystallization and become unclear. Pen as scale, it is ~15cm long.

4.2.6 Pulai

Pulai area is concentrated with the active quarry industries recently (Figure 4.50). Outcrops are fresh and well exposed here, but it is dangerous to get closer to the outcrop due to the risk of falling blocks. Hence, most of the field works are doing from distance or on the relatively stable outcrop e.g. gentle limestone outcrop.

Figure 4.50 Mining activities are still active in Pulai now. Those activities exposed many new and fresh outcrops.

The limestone is again similar to the other localities, highly crystallized and fractured. The dipping of the limestone range from gentle to almost vertical with striking NW-SE. Conjugate fracture set has been found on the outcrop at road side (Simpang Pulai-Cameron road, 1km), it cross-cut the whole limestone hill with high dipping, so it has been interpreted as late normal faults (Figure 4.51). Since the strike of the normal faults is in ~N-S, so it can be induced by E-W extension.

The limestone-granite contact is well preserved in the outcrop of Pulai. The limestone beddings are truncated on the granite, which could be indicated that it is not normal intrusion and the limestone was probably thrust on granite (Figure 4.52).

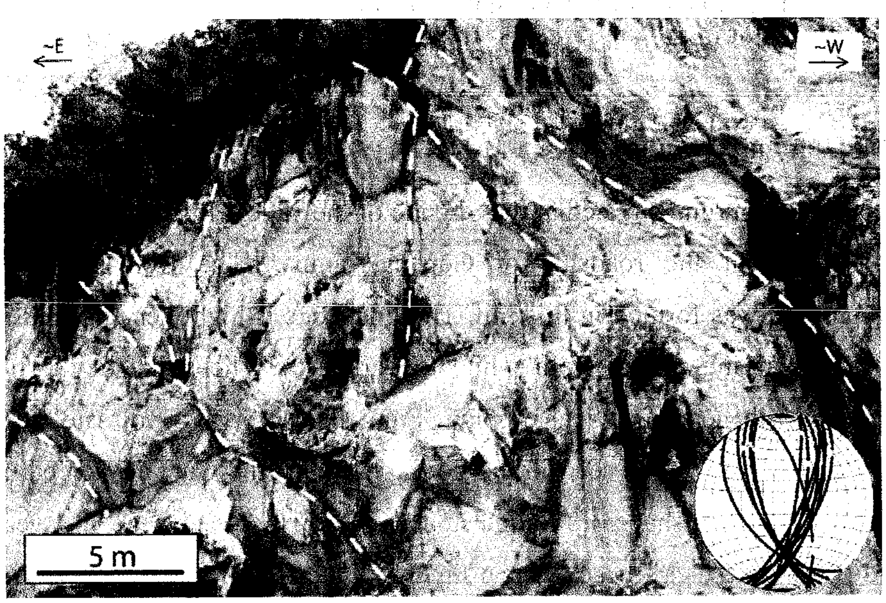


Figure 4.51 N-S striking conjugate fractures (yellow dash lines show one of the examples) found on the cliff of the limestone hill. Based on its high dipping angles, the fracture set is interpreted as the extension normal faults.

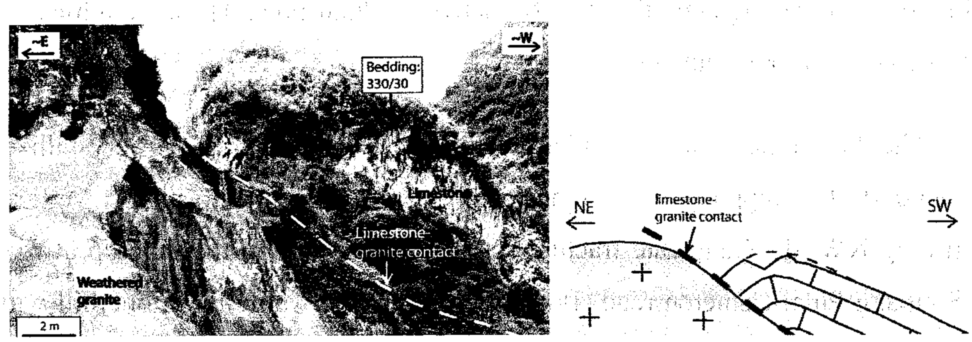


Figure 4.52 Limestone-granite contact found in the Pulai area. Granite is highly weathered and transformed into white-coloured kaolinite at the left of the image. The limestone hill is covered by thick vegetation except the cliff face, which is located at the middle of the image. The cartoon at the right illustrated the orientation of the limestone and granite in the image. The limestone is truncated on the granite indicating that it is not only a normal intrusion.

4.2.7 Gunung Tempurung

Gunung Tempurung situated at the SE side of the valley. It is next to the Main Range, and located at the roadside of Gopeng-Kampar. The well known cave, Gua Tempurung, was formed in this hill. The limestone is highly crystallized and formed bands in varying colour from white to dark grey. The strike of the beds is N-S direction with nearly vertical dipping. From the observation of satellite image, the fold of the limestone is seen in the northern end of the Gunung Tempurung (Figure 4.53) based on the shape of the limestone bars. This fold has been later verified in the field (Figure 4.53A). These vertical limestone bars (Figure 4.53B) represent bedding. It may be clearly observed near the entrance of Gua Tempurung.

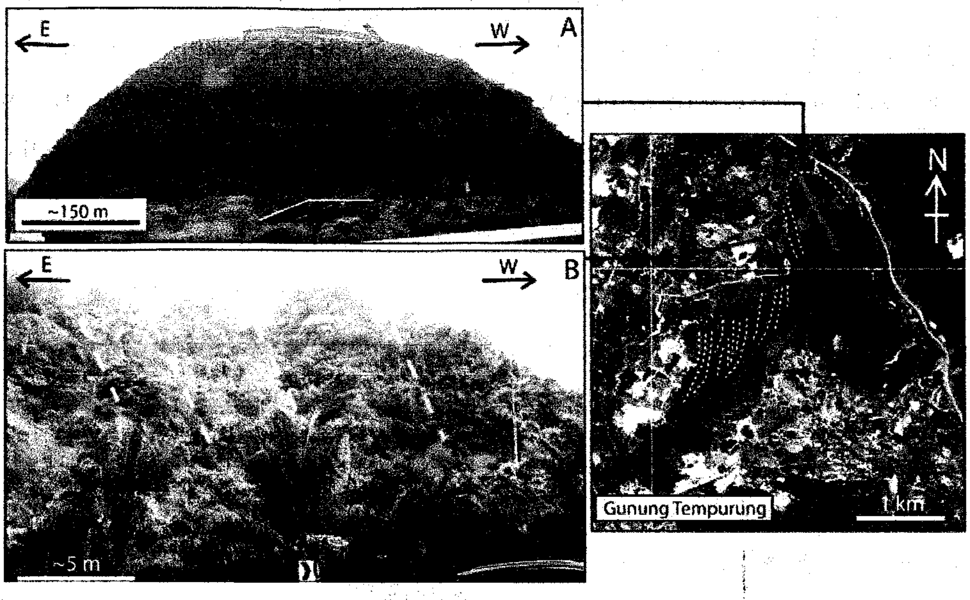


Figure 4.53 Limestone bars (yellow dash lines) and fold (green lines) in the Gunung Tempurung, as observed on the satellite image and in the field. [A] The round top limestone peak is interpreted as the fold of the limestone, formed nearly N-S anticline. [B] Limestone bars (represented beddings) formed near the Gua Tempurung, which are compatible with the lineaments found on the satellite image.

4.2.8 Sungai Siput

Sungai Siput is located at the northern part of the Kinta Valley. Limestone forms some of the peaks of the hills. Coring in the limestone has been conducted recently in order to study the subsurface limestone formation by UTP researchers.

From the observation on the cores, the limestone formation is composed of light to dark grey-coloured beds and commonly folded (Figure 4.45A). The folds are likely to be syn-sedimentary structure or slumps. But a bed in the fold shown brittle deformation (tension faults) which means the fracture formed when the limestone already harden and behaves brittle. It is not likely to be seen in the syn-sedimentary environment which still composed of un-consolidated, cohesive and soft material. This structure has been deformed in brittle manner or tectonic event, and its formation needs further study with more data and field observation.

Conjugate fractures have been observed in the core (Figure 4.54B). It just formed in certain beds which were probably more competent and vanished in the next bed. It is likely to have formed in syn-sedimentary environment. The fractures may have formed due to the overloading in the basin, with competent beds consolidated and easily deformed in brittle manner (fractured).

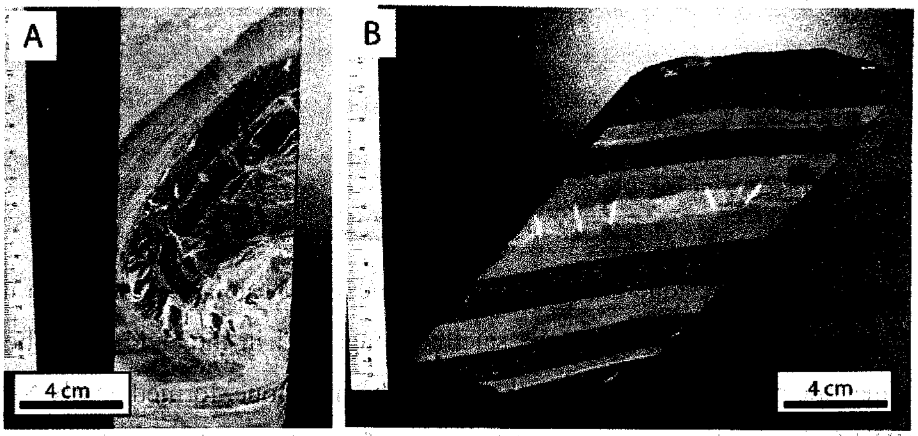


Figure 4.54 Limestone cores of Sungai Siput. [A] Limestone beds folded in S-shaped. Tension faults (red arrow has marked one of them) formed in the darker bed. It shows that the bed is more competent. [B] White beds of the core consist of fractures which marked by yellow lines, the fractures vanish at the next bed. The similar fractures can be observed at the first bed of the core from top.

4.3 Measurements in the Granite

Granite is the lithology widespread in the Peninsular Malaysia, and existed as the flanks of the Kinta Valley. The fractures are easily found in the granite due to its high competency and resistant weathering. Fractures occurred at all scales from region (satellite imagery) to outcrop, probably even in microscopic. The deformations were recorded by fracture patterns occurred in the rock. The structural study was mainly concentrated at the regional-scale, through lineament analysis at the digital elevation model of the SRTM, accompanied with the fracture analysis at the outcrop-scale in the selected sites.

4.3.1 Regional-scale Fracture Sets

The fractures or lineaments are extracted from the digital elevation model of SRTM (90m resolution) with slope shader and global shader (Figure 4.55). The two shaders provide a clear lineament appearance and make the lineaments extracting easier. The extracted lineaments are mainly negative and they are usually rivers or valleys. So, these negative lineaments are commonly represented by the major fracture sets which controlled the local drainage patterns. The map below (Figure 4.56) showed that the granite batoliths have high density of fractures. The extracted lineaments or fractures have been plotted in rose diagrams (Figure 4.56 & Appendix 1) and to illustrate the dominant orientations of the major fracture set for further interpretation.

The three lineament sets or fracture sets found in the granite, which strike E-W, NW-SE and N-S. The E-W and NW-SE fracture sets occasionally cut through the granite boundary. The ENE-WSW and NW-SE fracture sets are apparently formed as a conjugate fracture set which indicated E-W compression (Gobbett, 1971), which similar to the discovered fracture sets: E-W and NW-SE sets. From the interpretation of Gobbett (1971), right-lateral shear could be expected on the ENE-WSW fractures, whereas the left-lateral shear should be seen in some of the NW-SE fractures, in order to underline a compression in E-W direction. The long and straight lineaments formed at the margin of the granite could have acted as faults which behaved as simple shear and/or strike-slip movement.

In the Main Range, N-S striking fractures are mainly dominant at the or near the granite boundary. It is interpreted to have occurred in compressional condition and the granite near the contact has been slightly folded. Eventually the granite is broken at the edge of the fold, and formed the parallel valleys. Away from the contact, the N-S fractures are become less dominant, at around 10km towards east from the granite contact. These N-S fractures commonly show normal fault movement, and were probably reactivated by the later deformation.

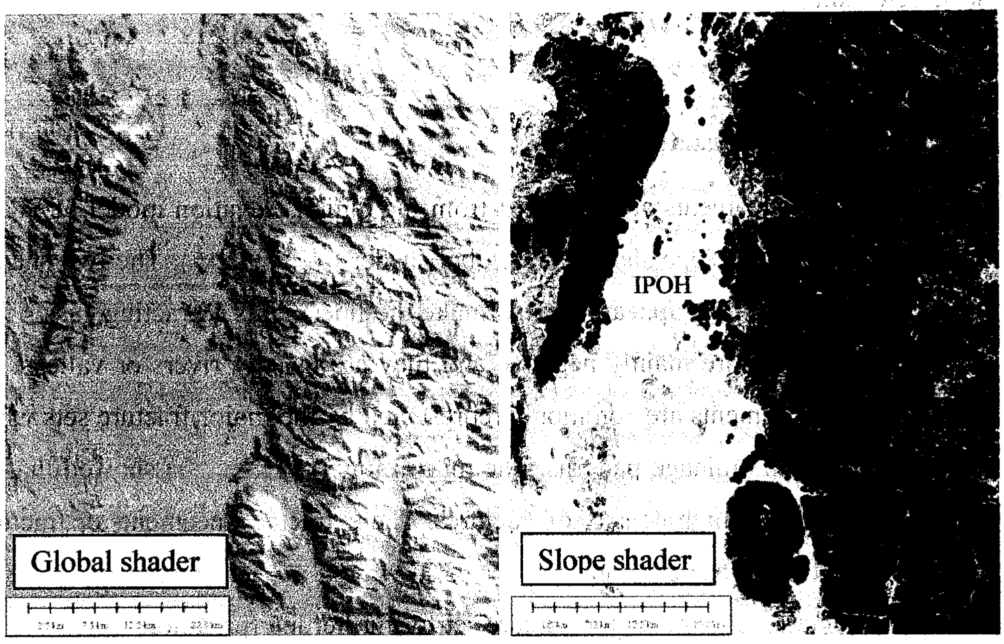


Figure 4.55 The lineamants formed in the granite, are well shown in the two shaders (Global shader and slope shader) on the digital elevation model of the SRTM.

4.3.2 Outcrop-scale Fracture Sets

Two sites have been selected to study the fractures in the granite of the Kinta Valley based on their accessibility. The granite outcrops have been chosen to study are Lubuk Timah and Keramat Pulai, which are located 1km and 3km of the Simpang Pulai – Cameron Highland road respectively. The fractures are compared to the fractures at regional-scale and make the further interpretation. These fractures are divided based on their strikes or azimuths. Three major fracture sets have been recognized in the granite; which are NE-SW, NW-SE and N-S.

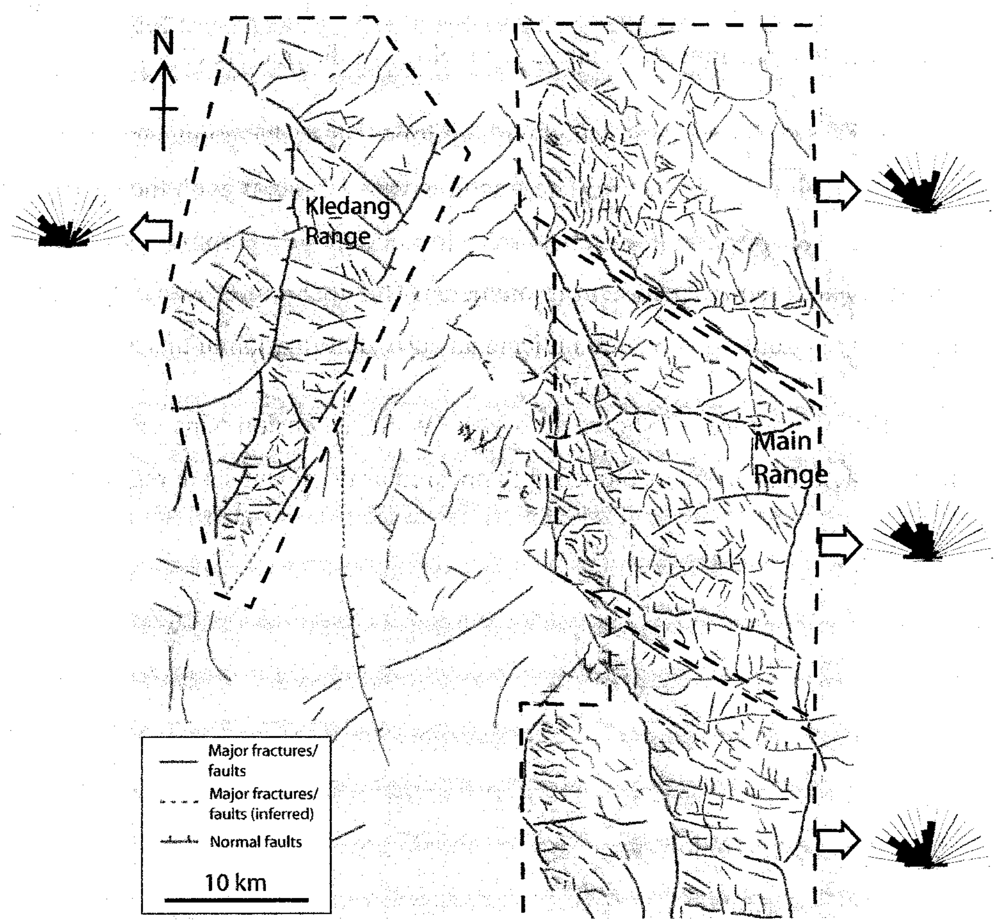


Figure 4.56 Faults and lineaments extracted from the digital elevation model. The rose diagrams presented the fractures existed within the respective dash boxes.

NE-SW fracture set

This fracture set is found in both sites. The fractures occurred with high dips (~80°) and densely, but it varies in infillings. In the Keramat Pulai area, the fractures are found as veins (Figure 4.57A, 4.57B), thickness commonly in millimeters and sometimes reach 2cm, filled with feldspar. The veins have now weathered and form white-coloured, soft kaolins in background of the white-coloured with some black dotted, less weathered granite. This indicates that the granite originally contained high percentage of feldspar and some amphibole group minerals and later transformed into kaolinite now. The cross-cutting relationships between fracture sets are unclear, since the weathering has erased the veins profile and hard to find enough and strong evidences to determine the relative chronology of the fractures.

The same fracture set is found without infillings in the granite around hot spring in Lubuk Timah (Figure 4.57C). The fractures vanish quickly with the narrow ends, and acted like tension faults. It occurred in the granite porphyry with the feldspar phenocryst which reached 2cm in diameter. This fracture set is clearly cut by another sets (NW-SE and N-S), which indicate an early deformation in this area.

NE-SW fracture set shows an early NW-SE extension, since it is cut by another major fracture sets and also does not appeared as dominant set at regional scale.

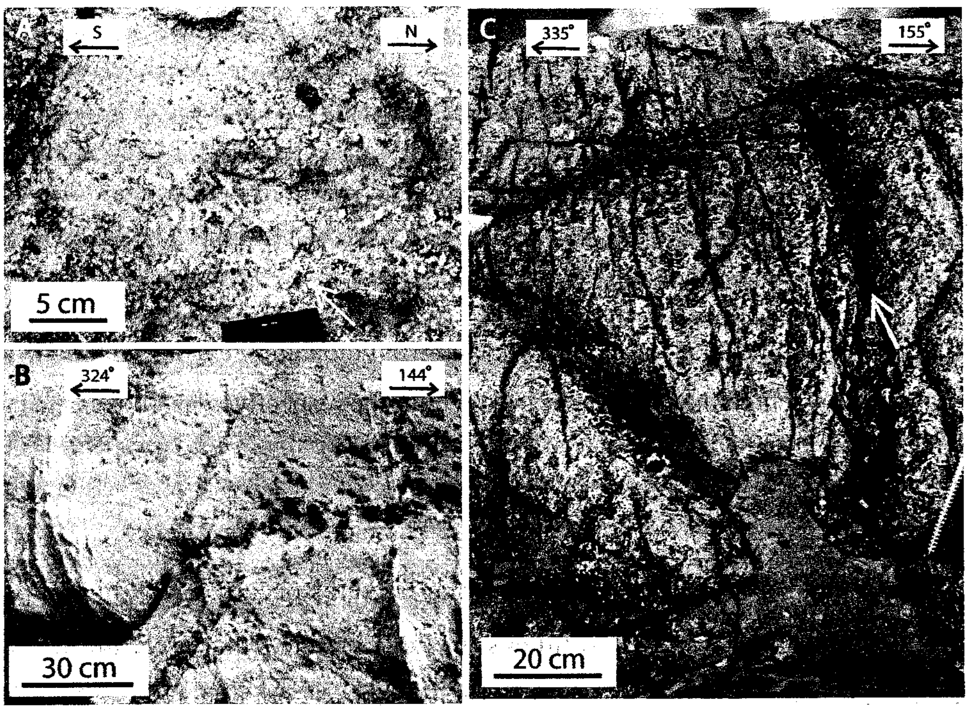


Figure 4.57 NE-SW fracture set found in [A & B] Keramat Pulai and [C] Lubuk Timah. The yellow arrows mark these fractures and also point to NE.

NW-SE fracture set

This fracture set is also found in both sites. The dipping of the fractures are more than 60°, commonly 80°. The density of the fractures are varies from outcrop from outcrop, especially in Lubuk Timah. These fractures are commonly without any fillings, it can be the normal faults or veins which filled with quartz.

The normal faults which are striking in NW-SE, have been observed in Keramat Pulai. The faults are almost vertically dipping (> 80°). The slickenside and Riedel fractures have indicated that the fractures are faults (Figure 4.58A). The slickenside is showed mixed black- and white-coloured clay which resulted from the weathering of the amphibole (black) and feldspar (white) mineral. The Riedel fractures are formed as tiny white-coloured veins which filled with feldspar. It probably indicated that the NW-SE feldspar veins which are common in the outcrop, are initiated by the NW-SE normal faults. The small pull-apart structure which was initiated by the normal fault (Figure 4.49B) is observed in the outcrop.

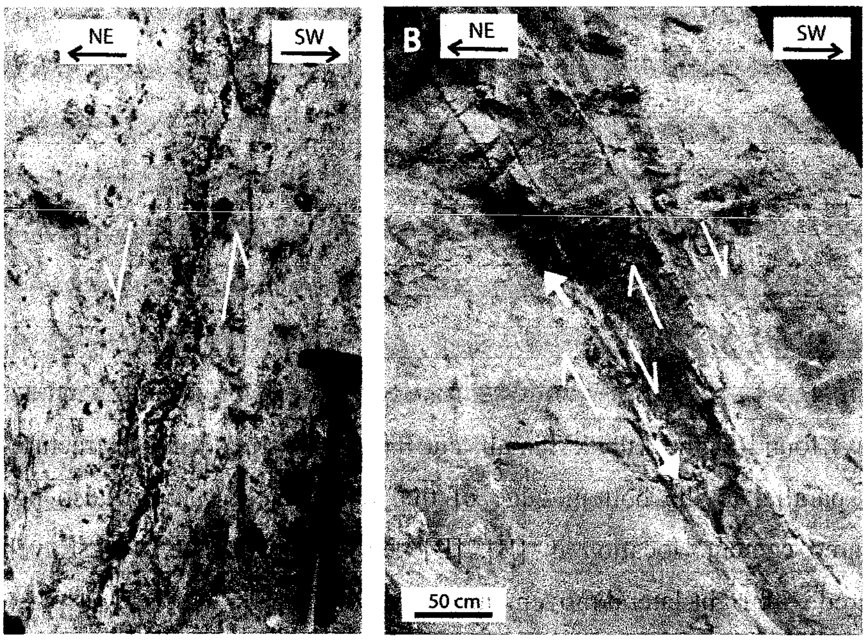


Figure 4.58 NW-SE fracture set or normal faults found in the granite outcrop in Keramat Pulai. [A] Dark-coloured slickensidess of the faults and high dips, light-coloured, thin Riedel veins can be observed around fault plane. Hammer as scale, length is ~30 cm. [B] One of the normal faults is open as a pull-apart structure (opening directions indicated by white arrows) and filled up with cement later.

Some of the NW-SE fractures formed as veins are found in Lubuk Timah (Figure 4.59A). The veins are filled with quartz with thickness in millimeters. These cement infillings of the veins are sometimes deformed into sigmoid shape by right-lateral shear (Figure 4.59B). The shear features are not commonly observed, so this movement is interpreted as local deformation which does not directly result from the regional tectonics.

NW-SE fractures are cut the other fracture set like NE-SW particularly can be observed in the granite outcrop beside Lubuk Timah's hot springs (Figure 4.50A).

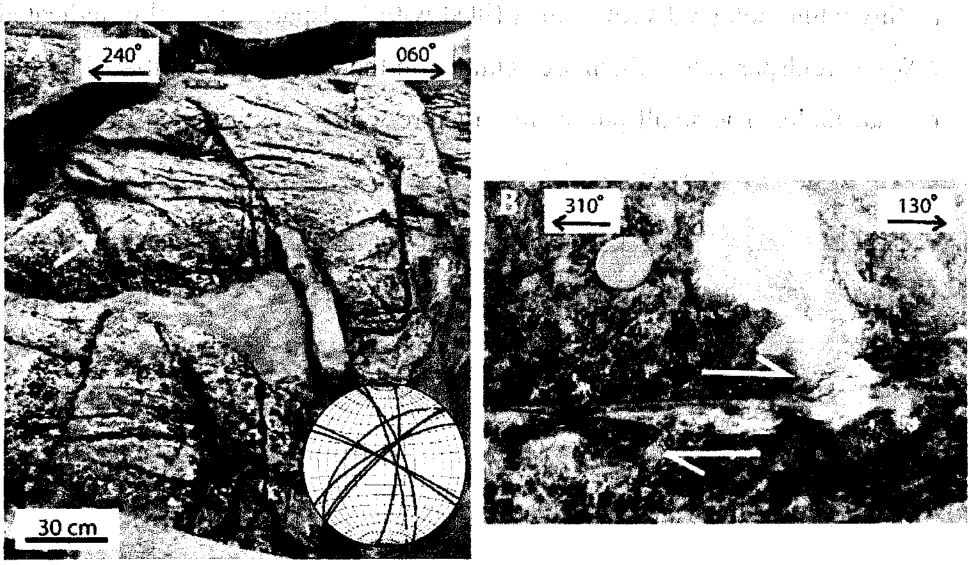


Figure 4.59 [A] NW-SE fracture set (one NW-SE fracture has been marked by yellow arrow) found in the Lubuk Timah, cut the pre-existing NE-SW fractures which are now parallel to the bottom edge of the image. Yellow arrow also points out the 'sheared cement' location in [B]. [B] The cement in the NW-SE vein has been sheared with right-lateral movement.

N-S fracture set

N-S fracture set exists as a minor set in both sites. It formed as feldspar or quartz veins in the Keramat Pulai in the highly weathered granite (Figure 4.60). The veins are highly dipping (> 70°). No clear cross-cutting feature is observed.

The fractures in the granite of Lubuk Timah are strongly dipping too. The density of the fractures is relatively lower than that of the NE-SW set. The occurrence is limited in certain outcrops. This fracture set does not have obvious infillings nor sense of movement. It cuts the NE-SW fractures, as indicated by late fractures.

Figure 4.60 N-S fracture filled with feldspar (veins propagate from bottom left to top right of the image) later transformed to kaolinite due to strong weathering. Notebook as scale (length of the notebook is around 20cm). The stereonet presented the fracture's distribution in site, and shows that the N-S fractures are less penetrative than that of the NE-SW fractures.

4.4 Measurements in Other Lithologies

The rocks occur sometimes locally or as minority and found in the foothill of the intrusion or edge of the valley. The rocks units include metamorphic rocks, clastic sedimentary rocks and side products of the granite (quartz porphyre, quartz veins and migmatite). I measured some characteristics of the rocks such as the strike and dip of the bedding, cleavages, faults, mineral containt, geometry and etc.

4.4.1 Tanjung Rambutan

Low relief area has been seen next to the Main Range in the radar and DEM. The corresponded lithology has been verified in the site and does not correspond to granite, but quartzite. The quartzite is fully affected by cleavages with orientation of 70/90. Part of the rocks has been found as cataclasite (powder-like) (Figure 4.61), due to strong crushing during faulting.

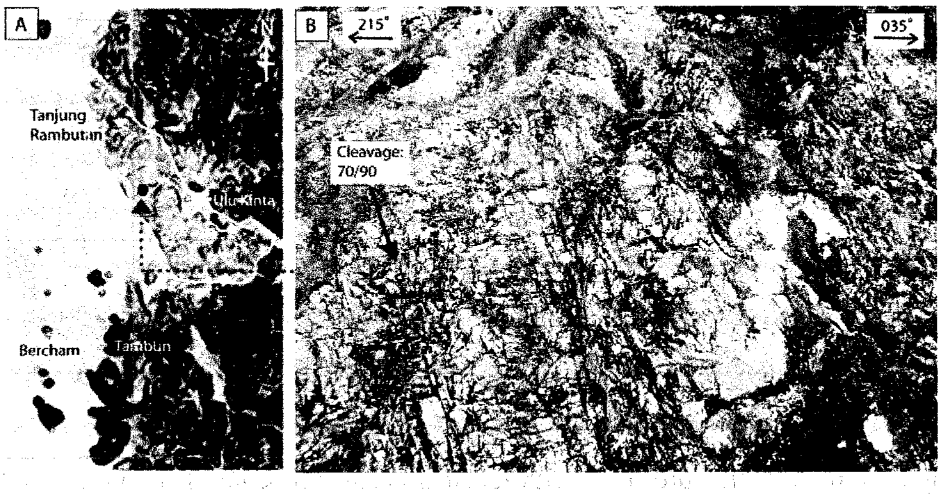


Figure 4.61 [A] Low relief area of Ulu Kinta, Tanjung Rambutan (bounded by yellow line) from DEM [B] Quarzite found in the area mentioned above. The cleavage is dense in the rocks. The white-coloured area surrounded by the blackish area at the bottom right of the image is powder-like quartz, produced by the intensive milling by faulting. Pencil near bottom left as scale, length is ~15 cm.

4.4.2 Jelapang

The outcrop is located in the opposite side of the Amanjaya Bus Terminal. The quartzite found in this outcrop and it seen similar to the one which found in Tanjung Rambutan. The orange-coloured highly weathered rocks are partially interbedded with the quartzite (Figure 4.62A). The weathered rock may have originated from the argillite such as mudstone or feldpatic rocks which easily weathered. The attitude of the quartzite is almost vertical and striking in N-S, although it is not clear (change of the lithology only). The cleavages are developed densely in the rocks with orientation 200/30 (Figure 4.62B).

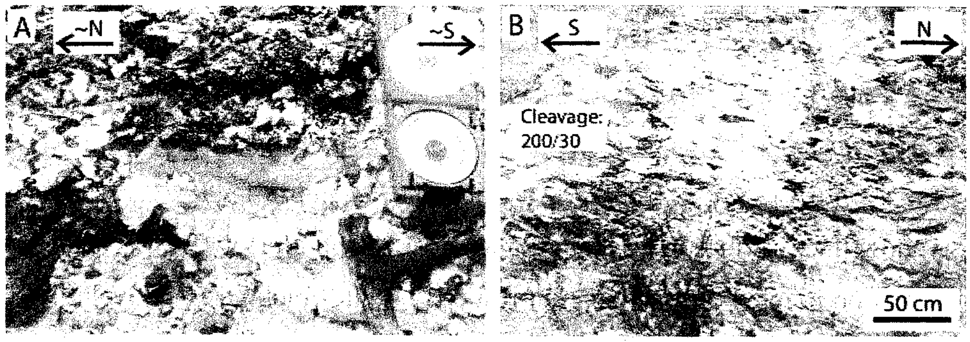


Figure 4.62 [A] Interbedded hard and soft rocks in the Jelapang's outcrop. The bedding is vertical. The hard part is quartzite and the soft part could be the fine-grained material which easily eroded. Compass as scale, length is ~20 cm. [B] The cleavages developed densely in the quartzite.

4.4.3 Chepor

An elongated ridge can be found in the radar image in the Chepor at the foothill of the Kledang Range (Figure 4.63A). It is actually a large quartz vein through the site visits and has currently been mined (Figure 4.63B). The dimension of the ridge is estimated in 100-200 m wide and several km long based on the radar image. The field observation of the southernmost of the ridge confirmed its dimension. The formation of this mega-vein could be the re-crystallization from the partial melting caused by the normal faulting along the intrusion surface.

The N-S striking nearly vertical fractures have been found in this quartz ridge and it cuts the rocks into sigmoid-shape. It shows brittle (Riedel fractures) or ductile structures (C-S band), the direction of the movement of the fractures cannot be confirmed (Figure 4.64). These vertical fractures are likely to contribute in shaping the steep slopes of the ridge.

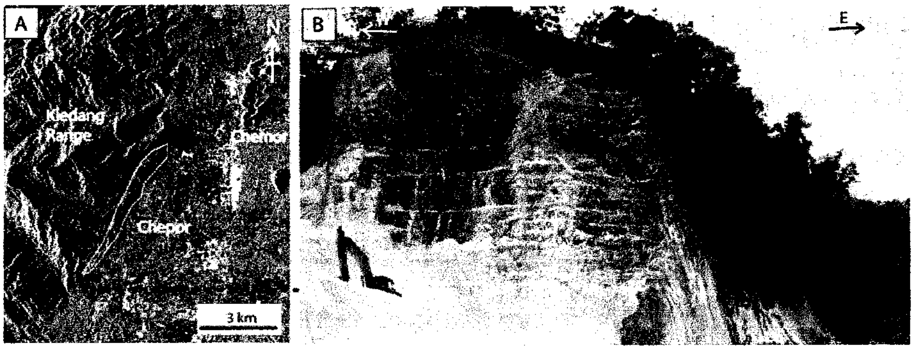


Figure 4.63 [A] Radar image showing the location of the ridge (bounded by the yellow line) next to the Kledang Range near Chepor. Image [B] was taken towards the direction pointed out by the red arrow. [B] White-coloured quartz vein in Chepor has a dimension of almost 100 meters wide and more than 1 km long. The ridge has steep slopes, and it stands out from the low plain because of its high resistant to erosion. Excavator as scale, length is ~ 10m.

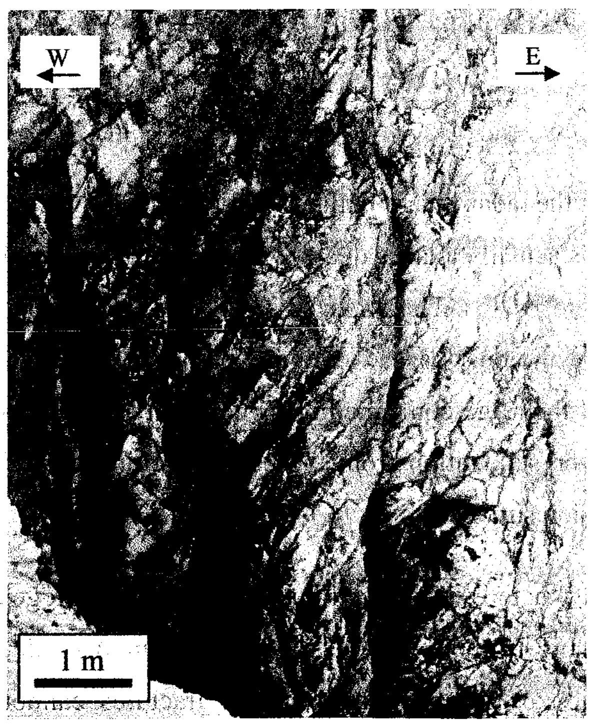


Figure 4.64 Fractures observed in the quartz vein. Most fractures are vertical and secondary fractures (within the major fractures) cut the rocks into sigmoid-shape. It is unclear whether it results from brittle (Riedel fractures) or ductile deformation (C-S band).

The quartz vein extends by few kilometers to the northern part according to the radar image interpretation. The outcrop shows mostly weathered rocks except for quartzite or rocks with high percentage of quartz. Migmatite can also be suspected in this area (Figure 4.65). In such case, the light-coloured quartz bands formed nearly parallel in the dark-coloured matrix would be the leucosome (chiefly composed of quartz), and the dark-coloured bands would be the melanosome (amphiboles). If proven to be correct from the thin sections, it would be formed by partial melting of the rocks deep underneath the surface.

Another outcrop near to the northern part of the ridge with a large fault gouge has been found in a steep slope has been found probably controlled by a large normal fault (Figure 4.66). The rocks are highly weathered but coarse-grained quartz can be easily found in the residual, indicating that it is formed in the final stage of the magma segregation. The thickness of the fault gouge is around 1m and filled with the light grey-coloured muddy materials. Both brittle and ductile deformations have been observed in the fault gouge, which are Riedel fractures (brittle) and C-S band (ductile). It is clear that the Riedel fractures are related to the normal faults. Based on the intersection way of the fault and C-S bands, the fault has probably experienced right-lateral strike-slip movement in ductile manner.

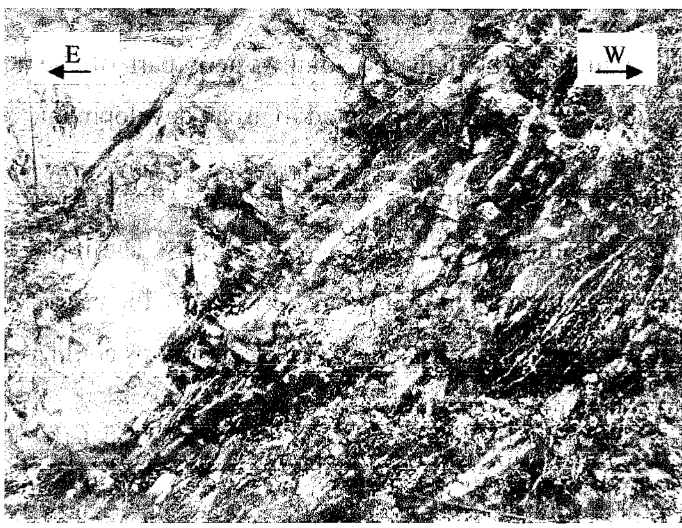


Figure 4.65 Weathered migmatite (?) found in the NE footshill of the Kledang Range, Chepor. Light-coloured bands are called leucosome which composed by granitic material and the dark parts are melanosome which rich in amphibole material. Red-coloured bag as scale, width is ~10 cm.

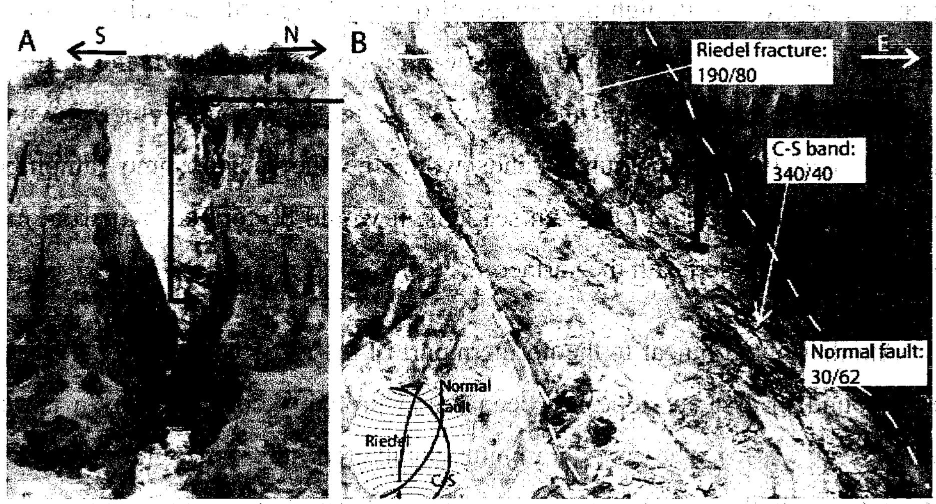


Figure 4.66 [A] Outcrops located at the northern part of the ridge as seen on radar image. The blue arrow point out the location of the image [B]. [B] Light grey-coloured normal fault gouge (area within white dash lines) which involved brittle (Riedel fractures) and ductile deformation (C-S band). Hammer as scale, length is ~ 30 cm.

4.4.4 Seri Iskandar

Seri Iskandar is a new city which situated in the southwestern part of the Kinta Valley. Outcrops such as roadcut, were freshly excavated to urban development.

In Seri Iskandar, the rock unit is composed of interbedded of sandstone and mudstone. The bedding is strongly dipping and striking almost N-S. The rocks were highly fractured. In the particular outcrops, fractures are in-filled by the reddish iron oxide and are a few millimeters thick, but the fractures in other outcrops could also be totally devoid of any in-filling. Conjugate fractures are one of the fracture sets (Figure 4.67A). It is similar to the fracture set observed in the Lost World and Banjaran, in terms of highly dipping, geometry and occurrence (fractures formed perpendicular to the nearly vertical bedding planes). After un-tilting restoration, the conjugate fracture set shows an ENE-WSW compression.

Another fracture set formed nearly perpendicular to the bedding plane (Figure 4.67B). This fracture set formed densely in the formation. It commonly offset the bedding plane by normal faulting. The displacements are not uniform and range from few millimeters to more than 5 cm.

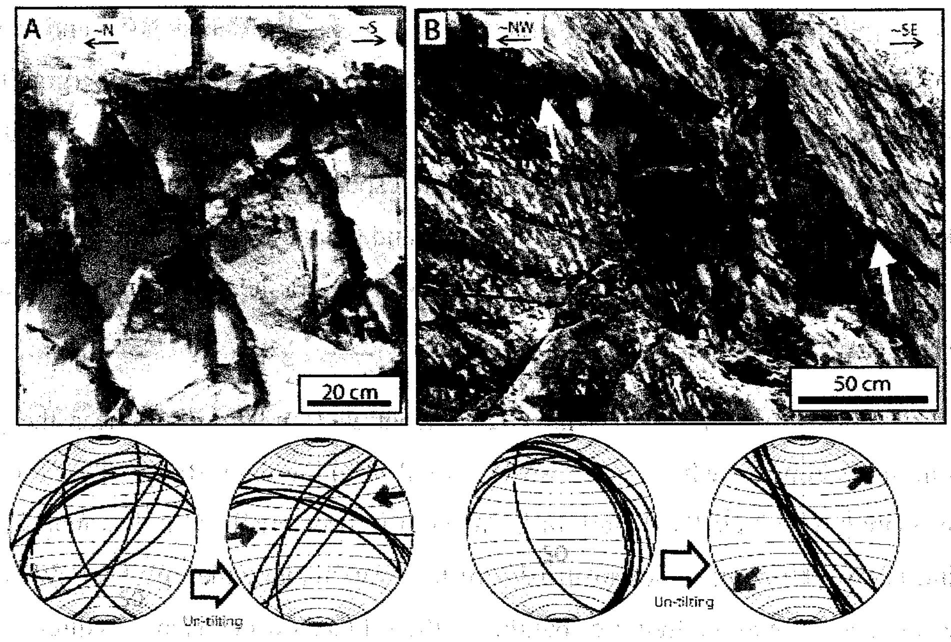


Figure 4.67 Two fracture sets found in Seri Iskandar. Stereonets at the bottom show the fracture sets before and after restoration. S0 is bedding plane. [A] Conjugate fracture set formed in the highly dipping beds and sealed by reddish iron oxide. It could be initiated by nearly E-W compression shown in stereonet when the bedding is still horizontal. [B] The fractures marked by the white arrows, displaced the bedding plane (cliff face). This fracture set is almost perpendicular to the bedding plane. The fractures may have originated from NE-SW extension.

4.5 Relationship of the Fracture Sets between Limestone, Granite and Other Lithologies

Granite has a similar fracture sets at regional-scale and outcrop-scale. The NW-SE and N-S fracture sets are found in both scales and the rest is ENE-WSW fracture set formed at regional-scale, whereas NE-SW fracture set has been observed at outcrop-scale. The high similarity of the fracture sets at different scales, indicated that this region experienced a unique tectonic event with minor local deformation.

At the regional-scale, the orientation of the fracture sets found in the limestone and granite are similar. These fracture sets are NW-SE and N-S, and a slightly deviation in the last fracture set, NE-SW (limestone) and ENE-WSW (granite). The fractures formed in the limestone such as strike-slip faults/conjugate fractures and thrust faults, are partially seen in the granite especially at eastern part of the Kledang Range. It could indicated that the limestone and granite were deformed together under the same E-W compression, but the fractures in the granite less expressed or modified by later deformation.

The N-S fractures in granite are concentrated and localized near the granite-limestone contact, where is the western foothill of the main Range. This fracture set was interpreted as the result of E-W compression applied at the margin of the intrusion. The competency properties of the granite make the tip of the folds broken easily and formed the fractures parallel to the fold axis which is in N-S direction.

Because of the bulk and rigidity of the granite body, the compression required to fracture the whole granite body is much higher compared to the one required for folding sedimentary rocks (limestone and clastic rocks). It means when both sedimentary rocks and granite were subjected to the E-W compression, the old and cold sedimentary rocks are more competent compared to hot incompetent granite, the limestone and clastic rocks were the first to deform through the formation of conjugate fractures and thrust faults. After the compression became stronger and the granite started to cool down, the granite became more competent and it fractured following a conjugate pattern (NW-SE and ENE-WSW), as a result of E-W compression. The continuation of the E-W compression then propagated in both granite and sedimentary rocks.

The E-W extension occurred following the E-W compression, and it represented by the N-S striking normal faults formed in the limestone. This event has affected the topography of the valley, which the footwalls in the fault are now high relief limestone hills, whereas the trough in between limestone hill probably represented the subsiding hanging wall, caused the limestone hills and the troughs to be all aligned in a N-S direction. The N-S normal faults may have reactivated thrust faults.

CHAPTER 5

SYNTHESIS AND DISCUSSION

5.1 Deformation Styles

We observed both brittle and ductile deformation. In terms of brittle structures, four fracture sets have been revealed in the limestone and clastic rocks. All the deformations are described as follows.

5.1.1 Early Set of Conjugate Fractures

Conjugate fracture sets that occur in two adjacent beds were observed on polished outcrops such as in the limestone cave of Banjaran Hotsprings, Tambun, eastern part of the valley (Figure 5.1). The conjugate fracture sets developed within beds of contrasting (competent and incompetent) rheologies and are highly crystallized. The fractures were found occasionally filled with white-coloured calcite and sometimes display offsets or step-like features. All fractures show steep dipping (>65^{o}) layer and strike N-S after unfolding. The similar fractures have been observed in limestone of Sungai Siput and sandstone of Seri Iskandar (Figure 5.1).

The fractures may have initiated at high angle in the competent beds and propagated into incompetent bed with a lower angle. These fracture sets could not be observed at the regional scale, suggesting that it was an early penetrative deformation at the scale of outcrop. It may have developed due to overburden within the basin, and may not be necessarily of tectonic origin. The conjugate fracture set that fall into this group is labeled as D1 throughout this dissertation.

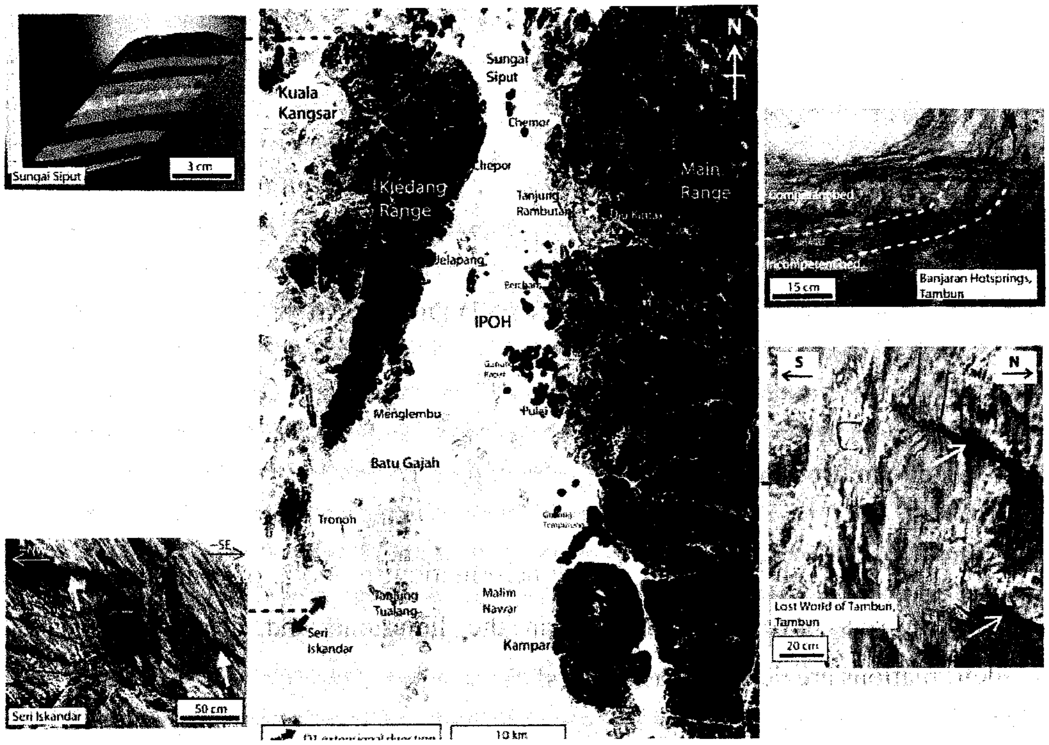


Figure 5.1 Summary of the locations where found the early set of conjugate fractures (D1) within the Kinta Valley. It also shows the extensional direction initiated by this deformation after un-tilting bedding. The core sample of Sungai Siput was not oriented, hence the extensional direction cannot be deduced.

5.1.2 E-W Conjugate Fractures

This fracture set occurs in both limestone and clastic sedimentary rocks (Figure 5.3). The conjugate strike-slip fault set in the gentle dipping limestone of Bercham show slickensides, which comprise dextral (E-W striking) and sinistral (NE-SW striking) movement with nearly vertical dip and horizontal pitch, likely due to ENE-WSW compression.

The E-W striking conjugate fracture set found in the vertical limestone of the Tambun, on the east flank of the valley, in both outcrop-scale and hand-specimen scale, is identical to the strike-slip fault set of Bercham after unfolded. Hence the overall structural style is showing E-W compression in the gently-dipping beds and in the restored vertical strata suggesting that the conjugate set was formed prior to folding, but within the same compressional direction. This conjugate fracture set is named hereafter as D2.

5.1.3 Thrusts

The faults found in the Tambun are thrust faults. Their geometry could be observed on both the satellite image and the outcrop. The triangular pieces represent thrust imbrications within a small wedge. Apparent strike of the fault is N-S direction, although difficult to measure, but the wedge propagated towards the granite was located to the east. The apparent dip of the thrust faults formed in the Tambun is around 30°.

The comparison in the direction of faults' propagation in Tambun and Bercham was shown in Figure 5.2. The faults at both areas were shown the similar propagation direction (ENE-WSW to E-W). The faults in Bercham were propagated to eastward and westward, with similar strike and low angle dip. It indicated a more complex deformation occurred here, which is back-thrusting. This thrust faults have been labeled as D3. Thrust faults are commonly folded the beddings. In fact, few folds (anticlines) have been observed in DEM in Kinta Valley, especially southern part, which probably was initiated by the same E-W compression (Figure 5.3). The occurrences of the indications of the E-W conjugate fractures (D2) and thrust faults (D3) have been plotted in Figure 5.3.

Figure 5.2 Comparison of fault's propagation direction in between Tambun and Bercham. The direction of propagation of the faults is marked by red arrow. The propagation direction of the faulting (ENE) in Tambun (east) is generally compatible with the fault's striation (ENE-WSW to E-W) at the limestone located at Bercham (west), as shown on the regional map (top).

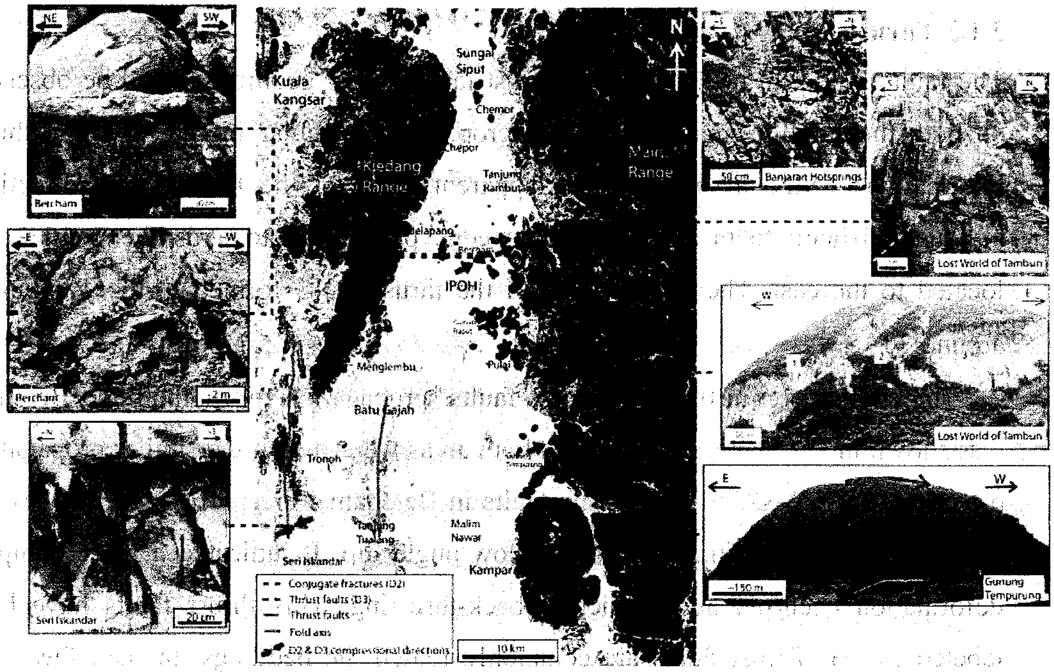


Figure 5.3 Summary of the locations where I found the E-W conjugate fractures (D2) and thrust faults (D3) within the Kinta Valley. It shows nearly E-W compressional direction initiated the deformation after restored the bedding. The compression has resulted in the formation of the N-S trending fold axes, perpendicular to the compressional direction.

5.1.4 Ductile Deformation

The 'slump' structures were common in the limestone of the Banjaran Hotsprings in Tambun, and often correspond to syn-depositional gravity sliding of the cohesive carbonate sediment on a slope (Pierson et al., 2009).

However the centimetric to metric structures observed in the vicinity of the contact with the granite are different and seem to indicate a typical of ductile behavior, also metamorphosed shale (hornfels) with tight microfolds are formed at the contact. It could be related to the granite intrusion at both sides of the Kinta Valley (Main Range and Kledang Range) formed during Late Triassic to Early Jurassic as determined by radiometric dating (Bignell & Snelling, 1977; Darbyshire, 1988; Krahenbuhl, 1991).

When the granite intrusion came in contact with limestone, it was still at high temperature and baked it. This is attested by the ductile deformation of previously formed veins which cut the limestone beds as when they were already indurated (Figure 4.37). As shown in the Figure 5.4, the relatively thin, dark-coloured layers present in the pure limestone underline a top-to-the-left simple shear. Interestingly, where ductile deformation takes place, it overprints the previous brittle structures, which remain only as relicts, and therefore the marble appears very homogeneous. It is of course very likely that slumps structures also existed prior to the high temperature (HT) deformation.

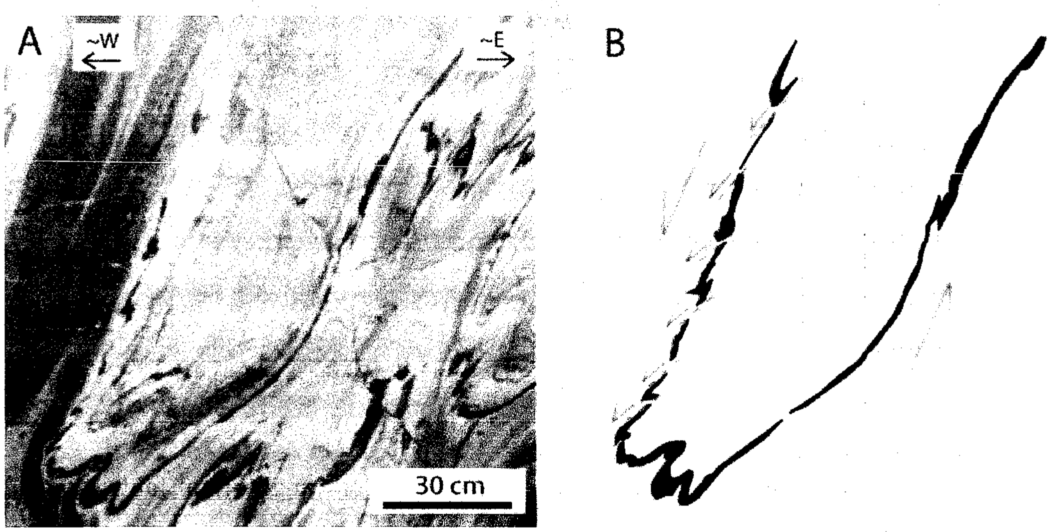


Figure 5.4 [A] Slumping-like structures observed in the meditation cave of Banjaran Hotsprings, Tambun, indicating ductile deformation. [B] The scratch of the limestone bed in [A] has small normal faults on the bed boundary, showing the ductile behavior of this layer with left-lateral simple shear.

5.1.5 N-S Striking Normal Faults

The occurrences of the conjugate normal faults have been summarized on the map (Figure 5.5). Normal faults strike N-S with high dipping angle and occur in limestone hills, granite and schist at regional- and outcrop-scale. This conjugate fracture set was interpreted extensional, although the displacement across the structures was never noted. Normal faults were identified based on the following evidences, (a) it has high dipping angle and, (b) the large exposure area of extraordinary smooth fracture plane. An E-W extensional direction can be deduced based on the dipping direction of the faults.

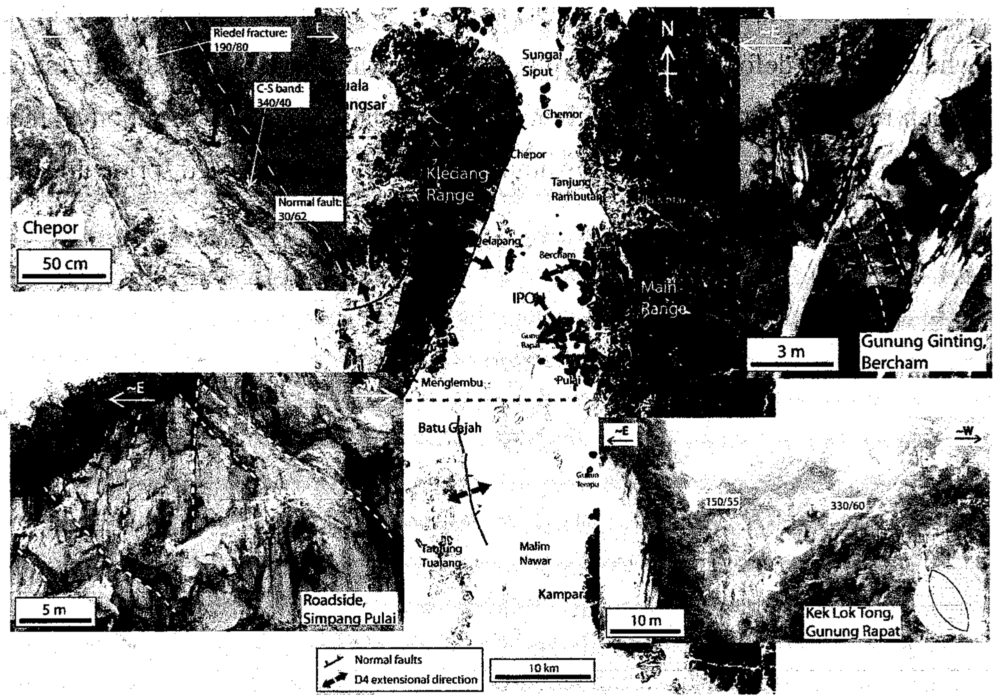


Figure 5.5 Summary of the occurrences of the N-S striking normal faults (D4) in the Kinta Valley.

This fracture set is probably a late deformation, because it often propagates through the whole outcrop and cross-cut other fractures. The narrow valley/lineaments found in the limestone hills generally underline these normal faults. The average altitude of the blocks at both sides of the lineament is different, indicating block faulting or normal fault, (e.g. NW of Gunung Rapat, Figure 4.12A).

Because strikes are co-linear (N-S) for D3 and D4, these faults might reactivate former thrusts. These extension faults are labeled as D4.

The normal faults have been compared with the grabens that formed in the Strait of Malacca, show that their geometry, orientation and extension direction are similar (Figure 5.6). It means that probably a same extension event occurred and initiated the formation of the normal faults (Kinta Valley) and grabens (Strait of Malacca).

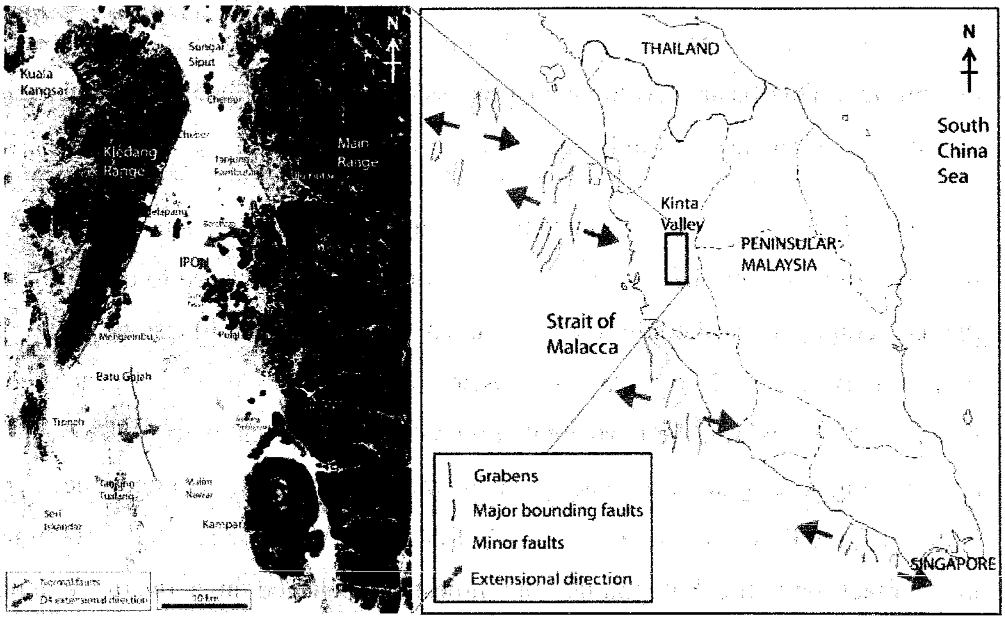


Figure 5.6 N-S strike of normal faults (D4) with respect to the grabens formed in the Strait of Malacca, in terms of orientation and geometry. They probably formed under the same extension event (pink arrows show the extension directions). Location map of the grabens in Strait of Malacca is modified from Liew (1995b).

5.2 Scenario

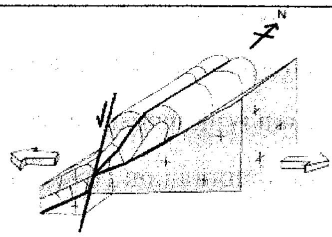
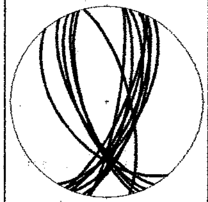
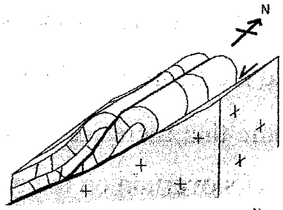
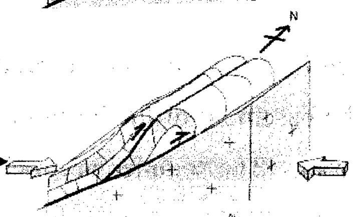
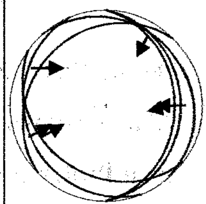
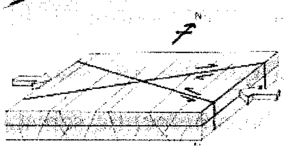
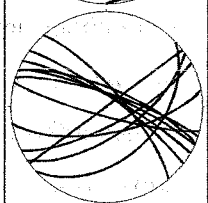
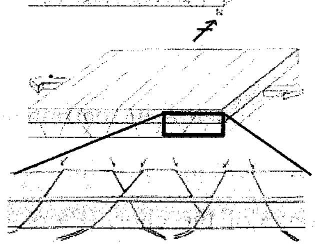
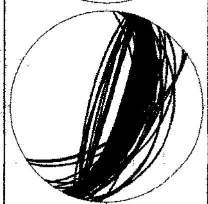
5.2.1 Structural History of the Limestone of the Kinta Valley

The structural history of the limestone was summarized in the Table 5.1. The carbonate sediments continued to deposited until Middle Permian (Suntharalingam, 1968), subsequently hardened, and broken into small brittle conjugate fractures due to overburden. This basin development process was active probably until the collision between the Sibumasu and Indochina blocks, during Triassic (Metcalfe, 2013).

The cessation of the magmatism by Early Jurassic (Krahenbuhl, 1991), was probably followed by the regional compression regime, which led to the formation of the D2 conjugate strike-slip faults or even folding of the limestone beds. Then, immediately after D2, the D3 compression occurred. D3 probably generated as a series of thrusts within the horizontal carbonate strata, which evolved toward the east approaching the granite contact. When the thrust sheets abutted the uplifting batholiths, the limestone became severely folded and vertical in attitude. 100m next to the contact with the hot granite, the limestone behaved in a ductile manner, as illustrated by localized flow structures and ductile pure shear. The ductile structures indicate normal movement, suggesting a gravitational collapse of the limestone parallel to the granite contact. The process would be similar to "roof-pendant" formation, but with high temperature (HT) conditions.

The extensional event D4 could be correlated with the Tertiary basement (horst and graben) of the Strait of Malacca (Liew, 1995b), the Mergui basins and onshore Tertiary basins of the Peninsular Malaysia, due to their similar orientation and structure. It would therefore date back from Eocene to Middle Miocene (Liew, 1995b).

Table 5.1 Summary of the structural deformation sequences in the Palaeozoic Limestone of the Kinta Valley.

Age		Deform. stage	Deformation model	Stereonet
Quaternary				
Tertiary		D4		
Cretaceous	Late			
	Middle			
	Early			
Jurassic	Late			
	Middle			
	Early	dd * D3		
Triassic	Late	D2		
	Middle	D1		
	Early	D1		
Permian		D1		

* dd: Ductile deformation

5.2.2 Tectonic Evolution and Development of the Structures of Kinta Valley

The scenario of the tectonic evolution is constructed based on the following information and assumptions:

1. Limestone is older than granite.
2. Granite intruded Palaeozoic rocks except limestone, however it 'cooks'/metamorphosed the limestone.
3. The compression is along E-W direction.
4. Compressional deformation (folds) affects hot limestone, in both ductile and brittle manners.
5. Limestone is overlain on the older schist.
6. Sandstone and mudstone are older than limestone and schist.
7. We also assume that there were volcanic rocks and post-limestone sequences/ Triassic (?) rocks overlain on the granite.

During Permian and even older period, Kinta Valley was part of the basin in the Palaeo-Tethys. The basement of the basin probably composed of early Palaeozoic or even Proterozoic rocks. The sedimentary rocks such as shale, siltstone and sandstone were either deposited at the bottom of the basin, or acted as part of the basement of the basin. A huge quantity of shale was deposited at the bottom, then was metamorphosed and became pelitic schist. The schist that we observed in Batu Gajah nowadays.

The deposition continued with carbonate sediments, which formed on the slope indicated by syn-sedimentary structure or slumps and deep marine environment shown by the existence of the chert (Pierson et. al., 2009). The basin was contracted by subduction until Palaeo-Tethys has completely subducted underneath the upper plate. When subduction proceeds, volcanic arc was expected to be formed on the upper plate where not far from the subduction zone. Those volcanoes were connected to the magma chambers below.

Mesozoic sediments or post-limestone sequences could continue to deposit on top of limestone in the basin, e.g. volcaniclastic/pyroclastic sediments originated from the volcanic activity. The subduction process terminated by the collision of down-going plate carrying asperities such as remnant arc and caused the compression to deform the rocks and sediments in the nearby area. The cessation of subduction also terminated the magma supply to the volcanoes on arc. Volcanoes eventually die out. The products of volcanos such as pyroclastic rock, volcano's crater, and Mesozoic rocks, which exposed to the atmosphere began to erode and have totally vanished nowadays.

Due to the unloading process on the upper plate (erosion of volcanoes), the magma chamber underneath the surface began to uplift, in order to compensate the erosion. The uplifted magma chamber or intrusion happened at the same time as the compression. The rocks in the basin have been intruded and cooked by hot granite. At the same time, current E-W compression also affected the limestone, and the rocks away from the granite contact experienced compression in brittle manner (fractured), while the rocks closed to the contact were deformed in ductile manner.

Compression initiated conjugate strike-slip faults (observed in Bercham) and the thrust faults in the valley (e.g. Tambun, Bercham, Gunung Tempurung). Both faults deduced a nearly E-W compression. Thrust faults need a decollement layer at the bottom which incompetent or soft, in order to propagate. Shale or schist (e.g. Batu Gajah Schist) could be a suitable candidate for the decollement since they were overlain by the limestone. Schist and limestone were occasionally and locally interbedded (Ingham & Bradford, 1960). Thrusts in limestone brought a portion of the schist onto the bedding plane. This process can be repeated several times on top of each other and produced the sequences that similar to the interbedded limestone and schist.

Interbedded sandstone and mudstone of the Seri Iskandar (SW of the Kinta Valley), was assumed to be deposited before schist and limestone. Thrusts have transferred the old clastic rocks (sandstone and mudstone) on top of schist where occurred in Seri Iskandar. Parts of the clastic rocks were still underneath schist and limestone of the valley such as Batu Gajah area. These clastic rocks were highly deformed and sheared (Figure 5.12) as schists.

Granite was also affected by the compression. This is visible especially in the part near to the granite contact which experienced fast cooling and became brittle early. Granite located at the east of the Chemor and Tanjung Rambutan, composed of nearly N-S striking and vertical fractures. The fractures can represent the tension faults formed at the hinge of the gentle fold due to E-W compression. NE-SW and NW-SE striking fracture sets found in the granite (clearly observed in Kledang Range), have probably induced an E-W compression similar to the deformations found in the limestone of the valley.

Compression initiated thrusts which developed in form of fault propagation fold (Mitra, 1990). Tightly fold of the limestone has resulted in structures such as anticlines and synclines, and where found near the granite contact, e.g. Gunung Datok, Tambun (aerial photograph: Figure 4.2, model: Figure 5.9, 5.10). The syncline possibly corresponded to a blind thrust fault that existed under the surface (Figure 5.10). The compression also folded the Batu Gajah schist and Seri Iskandar clastic sedimentary rocks (fold axes interpreted in DEM: Figure 5.3, model: Figure 5.12). The fold of Batu Gajah schist can be extremely squeezed (just like pressing toothpaste) due to its easy deformable behavior (Figure 5.12). Regional compression probably not lasted for a long period, the structural style ultimately transformed into extension by subduction jump.

When the hot intrusion uplifted the granite, limestone near the intrusion (e.g. Banjaran Hotsprings, Tambun, Figure 5.4) slightly melted and deformed in a ductile manner. The partial-melted limestone slides down from the slope of the intrusion like roof pendant but in high temperature condition. It may also have been reactivated existing structures such as slumps.

Extension created normal faults in the valley. Those normal faults can be observed in various lithologies, from regional satellite image to outcrop. Normal faults strike NNE-SSW to NNW-SSE (Figure 5.6). The major normal faults have been observed in the foothill of the Kledang Range (e.g. Figure 5.11), which marked by long and straight lineaments. The limestone of the valley often occurred along the eastern side of the valley, probably due to the subsidence of the normal fault at eastern foothill of

Kledang Range, which caused the limestone absents from the surface of western valley.

A few smaller-sized normal faults have also been observed, e.g. faults of the eastern side of the Batu Gajah which controlled the drainage pattern, and multi-faults initiated topographic steps in NW of Gunung Rapat. The normal faults can be re-activated from the pre-existing fractures or faults such as thrusts. The geometry and orientation of the normal faults of the Kinta Valley are similar to the grabens in the Strait of Malacca after comparison (Figure 5.6), which indicated both of them may be formed under the same event.

In the overall structural setting in the Kinta Valley, limestone sequences are more squeezed at the northern part compared to southern part. This may correspond to the northward narrowing of the valley. The basement of the valley also became shallower toward the north. It is proposed that the stacking of the rocks within valley was controlled by the deep-seated thrust faults which connected to mechanical discontinuity at few kilometers depth. Thrust faults have transferred the adjustment or displacement of faulting into deep ductile crust. The overall view of the geological setting of the Kinta Valley is shown in Figure 5.13.

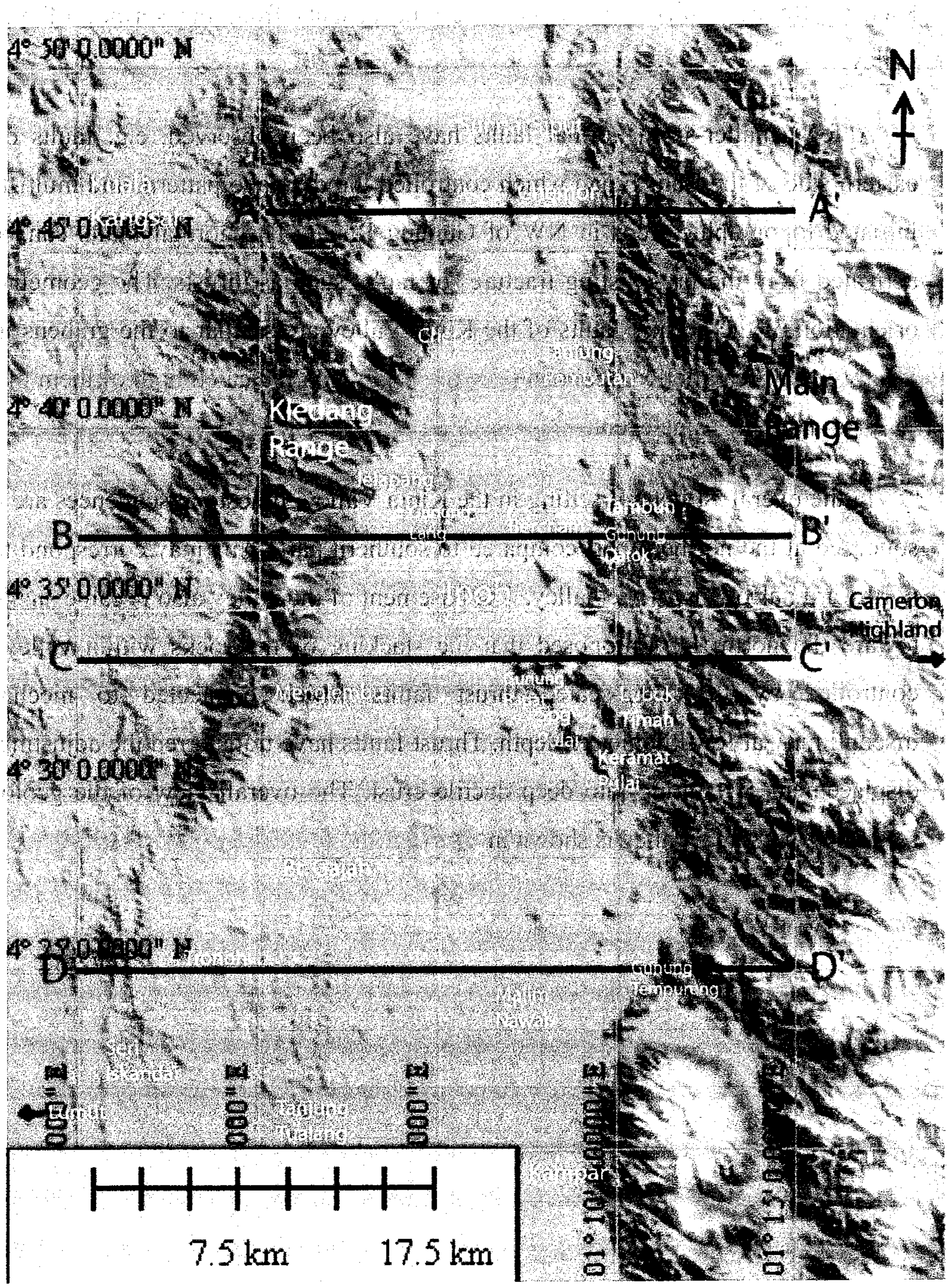


Figure 5.7 Map shows the location of the cross sections.

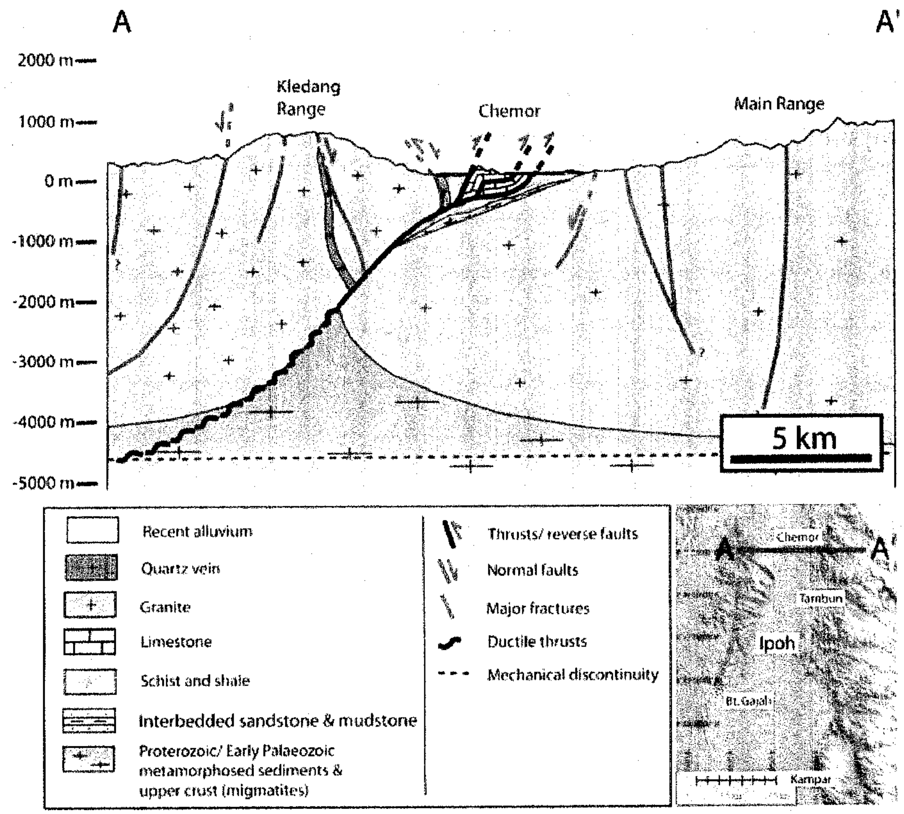


Figure 5.8 Cross section A-A’ of Chemor, northern part of the Kinta Valley. The valley is narrow and the limestone have been shortened, stacked and only found in the middle of the valley.

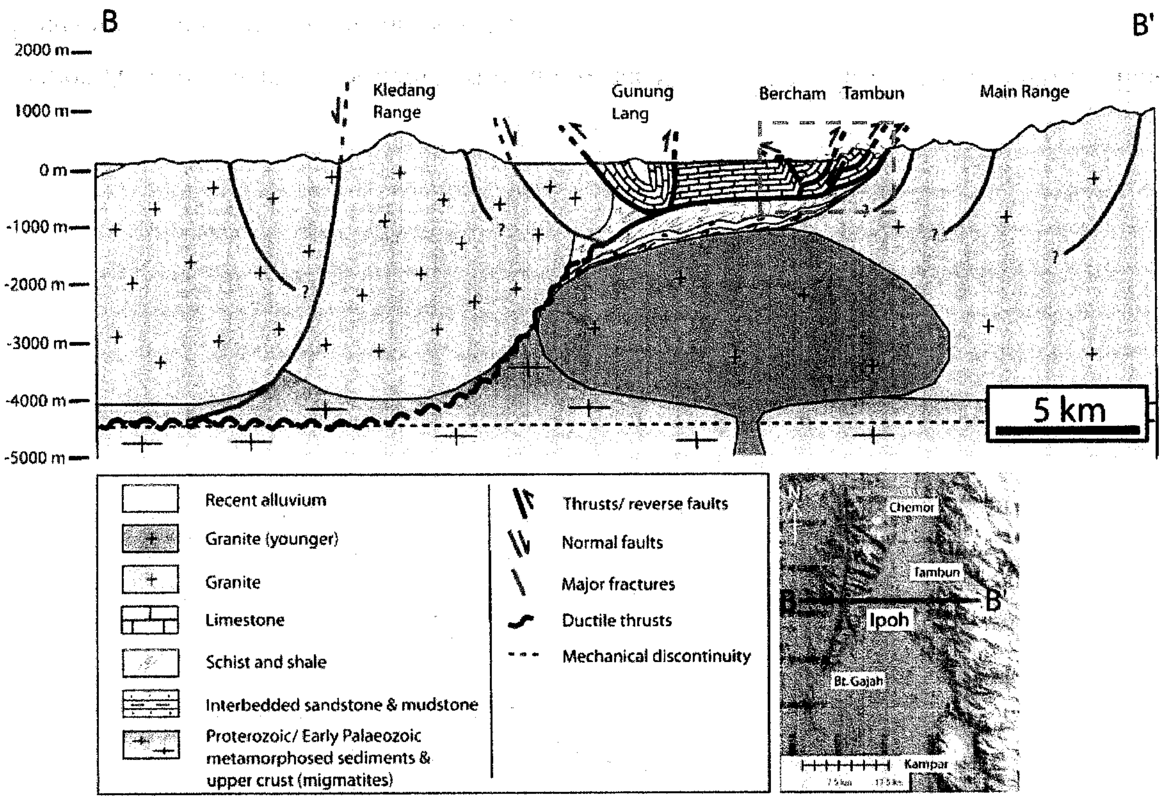


Figure 5.9 Cross section B-B' of Gunung Lang-Tambun area. The limestone has various dipping from the edge to the middle of the valley, caused by the thrust faults which connected deep into the earth. Few normal faults are found in the granite intrusion. Thrust near the granite contact has been zoomed in (orange box) and displayed in the Figure 5.10.

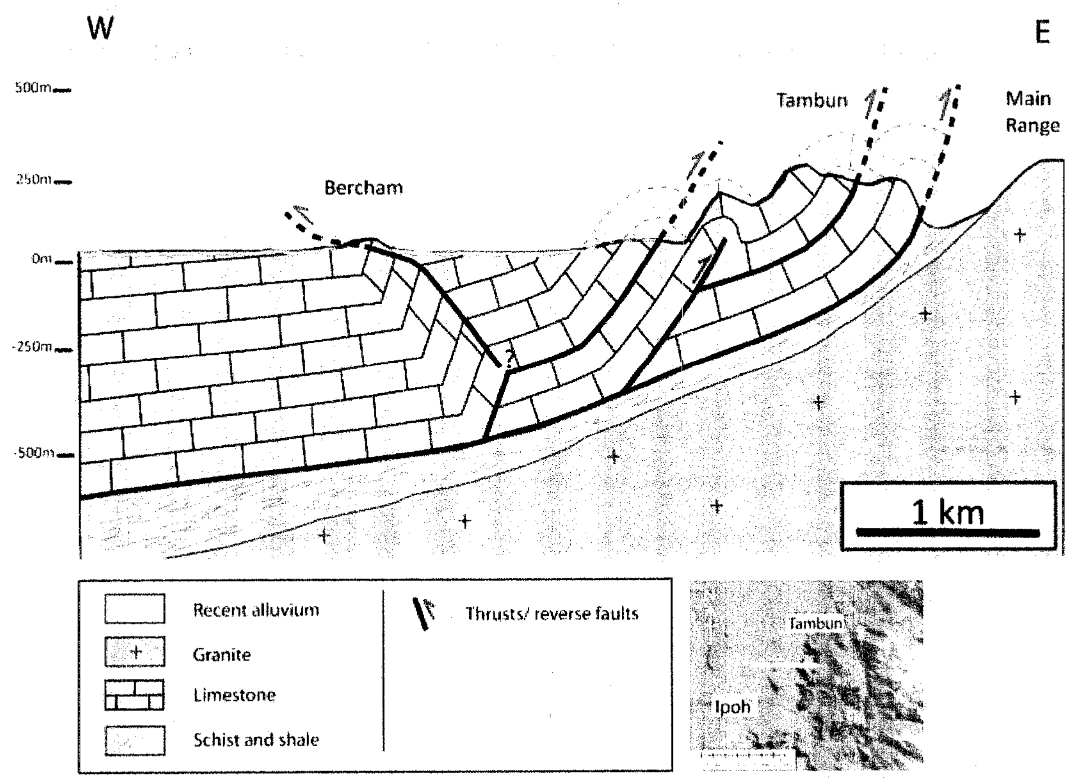


Figure 5.10 Tambun area's cross section. Thrusting tilted the limestone beds into vertical position at the foothill of the Main Range. Blind fault is believed to be found under the surface which corresponds to the syncline on top. Thrust of Bercham is interpreted as back thrust.

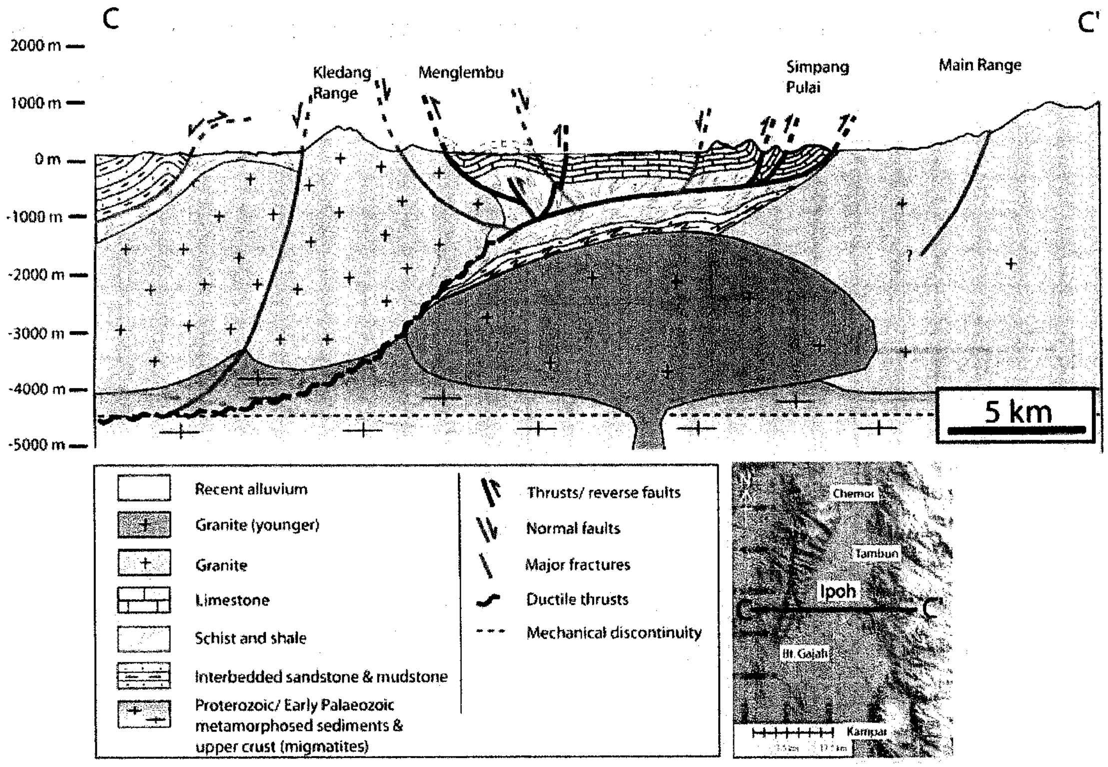


Figure 5.11 Cross section C-C' of Menglembu-Simpang Pulai area. The limestone beddings are steep at the edge of the valley and gentle at the middle of the valley. An unexposed granite intrusion located at the bottom of the valley is proposed.

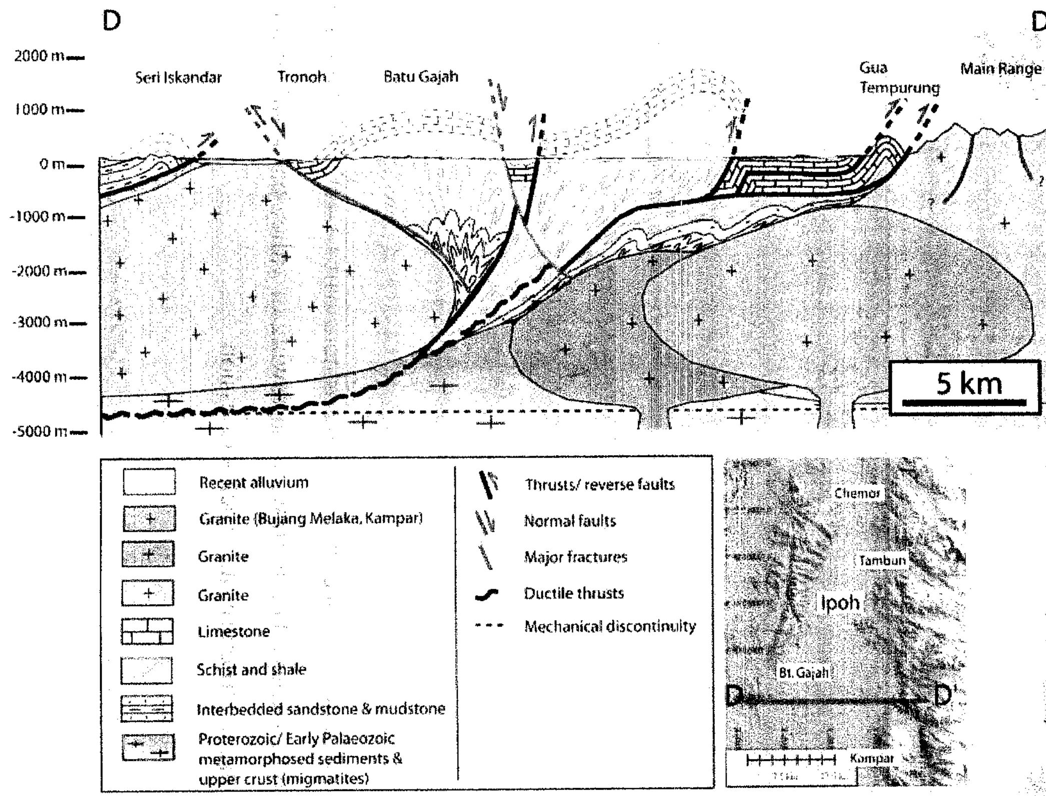


Figure 5.12 Cross section D-D' of Seri Iskandar - Batu Gajah - Gua Tempurung area. The limestone located at the western and middle parts of the valley almost totally eroded. The schists at the bottom are exposed at the west of the valley, and formed fold due to the thrusts. The limestone exposed to the east was thrusted towards the granite.

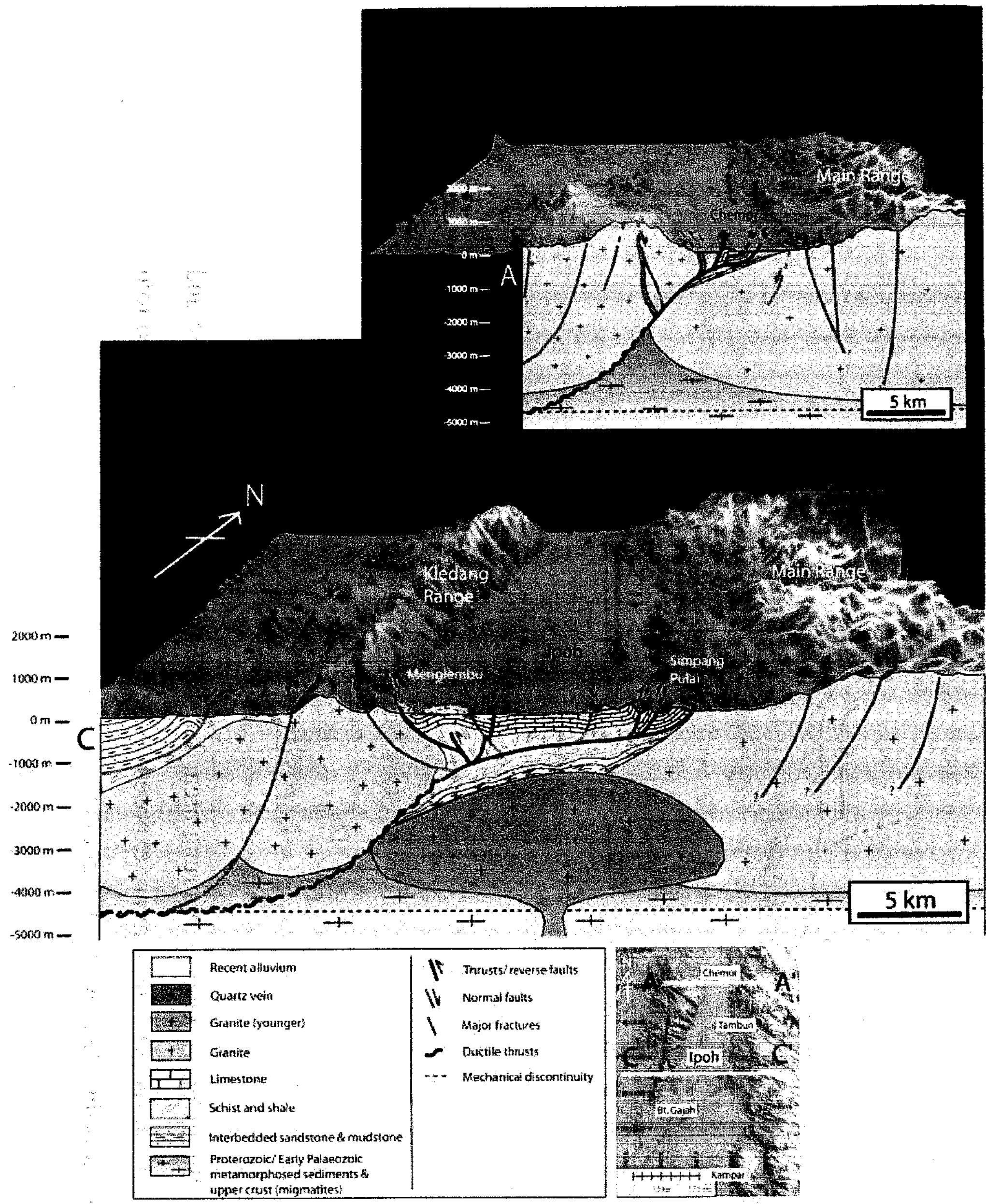


Figure 5.13 Two geological cross sections across northern part (A-A') and the south part (C-C') of the Kinta Valley. The northward narrowing of valley has resulted into more intense shortening in structures and rock succession.

5.2.3 Aquifers System

The fracture models illustrated the scenario for the formation of the Banjaran Hotsprings in Tambun. Before the model builds up, two other hot springs have been referred and compared, to identify the similarity and differences between these hot springs (Figure 5.14). The chosen hot springs are Ayer Hangat in Langkawi and Lubuk Timah near Keramat Pulai.

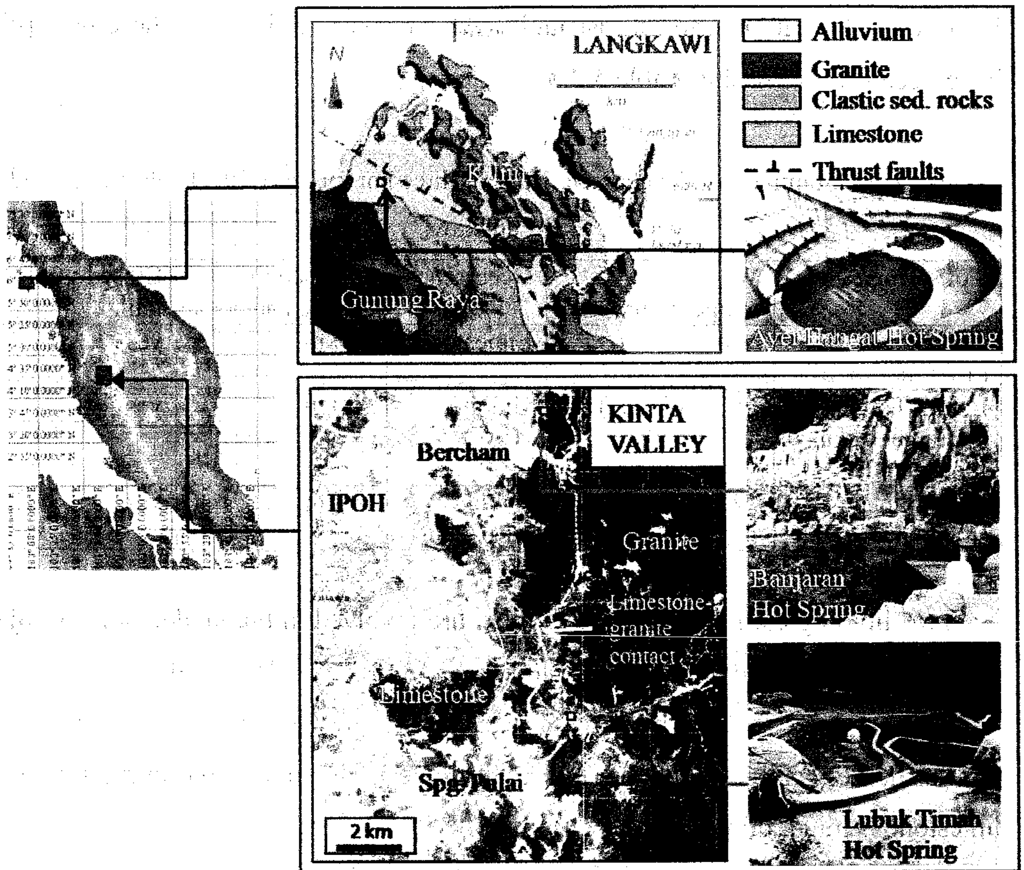


Figure 5.14 The location of three hot springs found in Kinta Valley and Langkawi.

Ayer Hangat Hot springs occurred in a muddy area of paddy field. It is different with the hot springs formed in Kinta Valley, which are limestone (Banjaran Hot Springs) and granite (Lubuk Timah Hot Springs).

In terms of spring water's temperature, Banjaran Hot Springs have the highest value (~70°C), followed by Lubuk Timah Hot Springs (~55°C), and Ayer Hangat Hot Springs have the lowest value (~40°C).

Both three hot springs are closed (< 1 km) to the granite contact, which can be the heat source for the hot springs. Ayer Hangat Hot Springs are also closed to a thrust (Kisap Thrust Fault). From the earlier observation and study, thrust faults have been identified in the outcrops of the Kinta Valley, which usually is the limestone-granite contact.

It indicated that the hot springs of the Peninsular Malaysia, at least partly, are likely closed to granite and thrust faults. All the characteristics of these hot springs have been summarized in Table 5.2.

Table 5.2 Summary of the characteristics of three hot springs of the Kinta Valley and Langkawi.

Hot springs	Water temperature (^{0}C)	Occurrence	Distance to granite contact	Close to thrust fault
Banjaran (Tambun, Ipoh)	~70	Limestone	< 1km	yes
Lubuk Timah (Keramat Pulai, Ipoh)	~55 (estimate)	Granite	< 1km	yes
Ayer Hangat (Langkawi)	~40 (estimate)	Muddy area	~1 km	yes

Two lithologies: limestone and granite, are involved in the model, since Banjaran Hotsprings are found near to limestone-granite contact. The model below (Figure 5.15) presents the fracture patterns formed in the limestone and granite. The sizes of the limestone's and granite's cubes are the same in the model, but in the reality, the limestone is much thinner than the granite.

Similar fracture orientations are found in both limestone and granite at the regional-scale and outcrop-scale. They are N-S, NW-SE and NE-SW. The cold surface water mainly supplied from rain fall, flows into the limestone through these fractures. The limestone is easily reacts with water and dissolved, and results numerous cavities on the surface and subsurface. Majority of the water in the subsurface of the limestone is in form of underground's river and water reservoir. Part of the water can penetrate deeper and reach granite. The fractures in the granite allow water to continue to penetrate further down to the hot section. As the water heats up, its density decrease, and it begins its way upward.

The conduits of the hot groundwater are different from those of cold water. The most possible conduits for the hot groundwater are thrust fault and normal fault planes which commonly cut deep inside (few kilometers) to the rock. The direct path behaved just like highway, which can decrease the rate of heat dissipation, keep the water still hot even emerge on the surface, and eventually formed as hot springs.

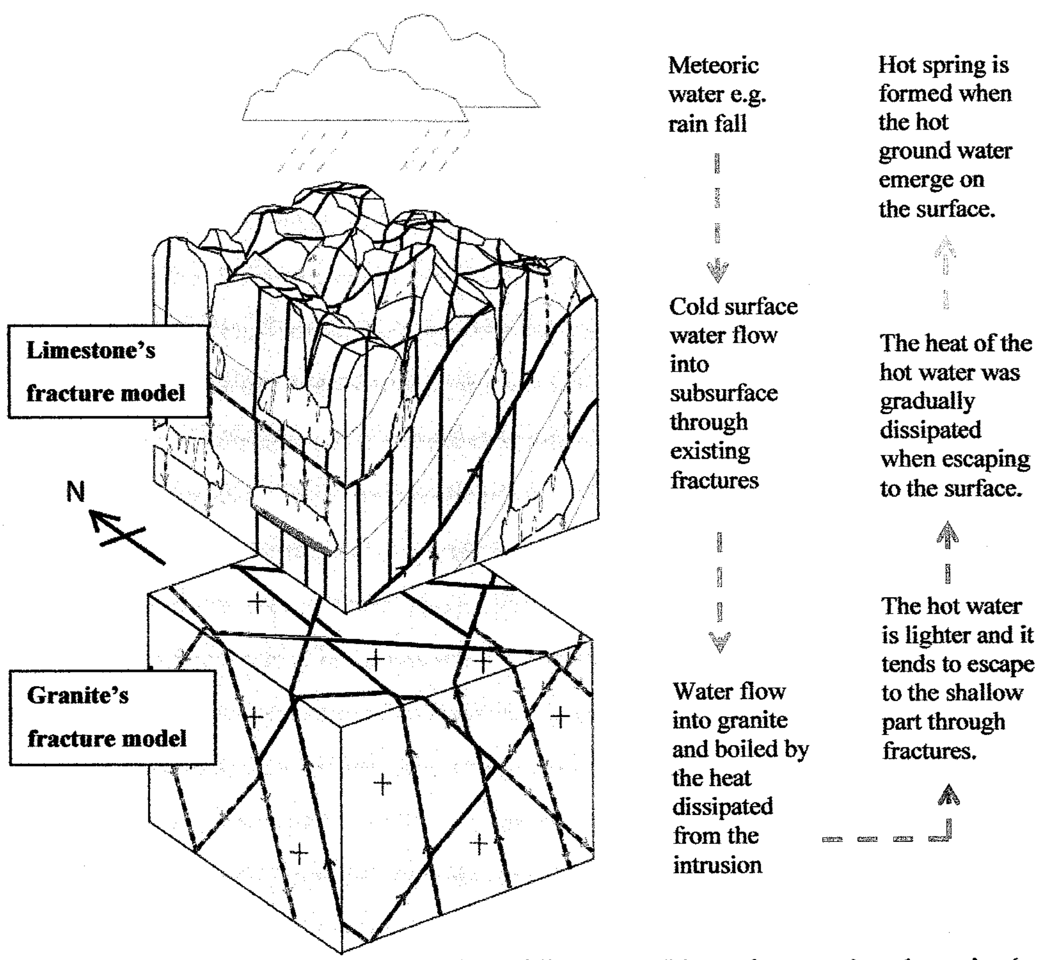


Figure 5.15 Proposed fracture model cubes of limestone (blue cube at top) and granite (red cube at bottom). The mechanism of the formation of the hot springs is indicated on the sidebar. Black thick lines are fractures; dash lines are water (blue = cold, pink/red = hot).

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

This study is focusing on the structural styles and tectonic evolution of the Kinta Valley. The analyses have been conducted at various scales, from remote sensing mapping, outcrop example, to microscopic observation, in order to understand the regional structural history. The observation and study are mainly on limestone, since it is the dominant and well preserved outcrop within the valley. Apart from limestone, deformation also affected other lithologies such as granite, schist/shale, quartzite and sandstone and mudstone. The resulting structures are similar to those of the limestone. Deformations are also included in the scope of study.

Both brittle (fractures) and ductile deformations observed in the Kinta Valley. The different fracture sets in the Kinta Valley are presented in a sequential pattern and used to trace its tectonic evolution. The regional deformation began with E-W extension which occurred after of the deposition of the carbonate sediment in the basin. The fracture set has been found in limestone of Tambun and Sungai Siput, also the sandstone of Seri Iskandar. It is represented by very penetrative micro normal faults (D1).

The extension changed into E-W compression which initiated the conjugate strike-slip faults (D2), thrust faults with tight folds (D3), probably after the end of the cessation of the granite intrusion in the Early Jurassic time. The E-W compression of D2 and D3, are believed to have caused the shortening in the limestone and resulted in the formation of tight folds and vertical bedding found at the edge of the valley. In southern valley, sandstone of Seri Iskandar and Batu Gajah Schist are also affected by the same compression, the beddings are tilted and formed fold.

When the shortening occurred, the limestone was in direct contact with the hot intrusion where the mobility increases because of partial melting, resulted in shearing, and ductile deformation. This deformation has been observed in the limestone outcrop of the Banjaran Hotsprings, Tambun.

E-W extension took place in this region after the D2 and D3. It is considered as late deformation which created ~N-S striking normal faults (D4). The similar normal faults have detected by seismics in the Strait of Malacca, which occurred as horst and graben with nearly N-S alignment.

All the deformations have affected the structural setting of the Kinta Valley. Nearly vertical beddings are commonly formed at the edge of the valley. The beddings are likely to be part of the N-S trending tight folds, which resulted from the strong E-W compression. The compression also initiated strike-slip conjugate faults and thrusts. Thrust faults mostly propagated to the east to the granite, but westward thrusting has also been observed, which suggested a back-thrust system.

Major rivers such as Sg. Kinta and Sg. Pari, exhibit drainage anomalies, the connected anomalies show a curved-shaped appearance, which may indicate the presence of the normal faults underneath. The normal faults probably followed the existing weak zone like thrust faults and granite-limestone contact. The valley is narrowing towards north, which may imply that shortening was more intense than in the south. Due to the relatively short distance between two granite intrusions in the northern part of valley, the bedrock is estimated to be shallower. The isolated rock units occurred in the edge of the valley have high probability to have formed near to the base of valley. For example, quartz veins in Chepor, at foothill of intrusion, could be formed by melting and recrytallization of the older sandstone.

The deep seated thrust faults and hot granite intrusion are the major factors for the formation of the hot springs in Banjaran. The proposed model stated that the groundwater has flowed into limestone and granite, heated up because of the hot intrusion, flowed through the deep seated thrust faults and eventually formed the hot springs at the surface.

6.2 Recommendations

The proposed cross sections have to be confronted to balanced restoration. It can be done with structural modeling tools, which helps reconstruct the initiation and development of the geological structures with all the characteristics such as depth, rheologies of the rocks, pressure and temperature, etc, taken into account.

Although the scenario for the tectonic evolution of the Kinta Valley has been proposed based on cross cutting relationships, it is not perfectly constrained in time. More data are needed in order to refine the current model.

Stratigrahic sequences of the Kinta Valley are still not well unraveled. The sedimentary rocks of the Kinta Valley e.g. limestone and clastic sedimentary rocks, are lacking of fossils, hence the ages of each rock units are ambiguous. Radiometric dating on the Batu Gajah's shale/schist is able to answer part of the question, which to validate one of the assumptions (Batu Gajah shale or schist is older than limestone).

In order to construct a reliable structural model, the subsurface setting has to be known. Geophysical study such as seismic, can visualizes the orientations of the strata and structures (e.g. fracture planes, fault planes, folds, etc) under the surface, it constrain the structural setting in model. Gravity and magnetic surveys provide the information of the rock properties such as density and magnetic anomalies. It helps in prediction of rock types, and also the mechanism of the deformations of the subsurface rocks which situated in depth with greater pressure and higher temperature.

REFERENCES

Abdul Rahim Samsudin, Umar Hamzah, Rakmi Ab. Rahman, Chamburi Siwar, Mohd. Fauzi Mohd. Jani and Redzuan Ohman, 1997. Thermal springs of Malaysia and their potential development. *Journal of Asian Earth Sciences*, 15, pp. 275-284.

Abdul Rashid Bachik, 1991. A preliminary study of the water quality and flow of thermal springs in peninsula Malaysia. Geological Survey of Malaysia. *Annual geological report 1991*, pp. 170-185

Ahmad Jantan, Basir Jasin, Ibrahim Abdullah, Uyop Said & Abdul Rahim Samsudin, 1989. The Semanggol Formation – lithology, facies association and distribution and probable basin setting. *Geological Society of Malaysia Warta Geologi*, 15, 28.

Areshev, E.G., Dong, T.L., San, N.T., Shnip, O.A., 1992. Reservoirs in fractured basement on the continental shelf of southern Vietnam. *Journal of Petroleum Geology* 15, pp. 451-464.

Barthrust, R.G.C., 1971. *Development in Sedimentology 12: Carbonate Sediments and Their Diagenesis*. Elsevier, Amsterdam.

Bignell, J.D. & Snelling, N.J., 1977. Geochronology of Malayan granites. *Oversea Geology and Mineral Resources*, 47, Institute of Geological Sciences, H. M. Stationery Office, London, 72pp.

Burton, C.K., 1973. Mesozoic. In: Gobbett, D.J. & Hutchison, C.S., (eds). *Geology of the Malay Peninsula*, Wiley-Interscience, New York, pp. 97-141.

Butler, R.F., 1992. *Paleomagnetism – from Magnetic Domains to Geologic Terranes*. Blackwell Scientific, Oxford, pp. 238.

Cardozo, N., and Allmendinger, R. W., 2013, Spherical projections with OSXStereonet: Computers & Geosciences, v. 51, no. 0, p. 193 - 205, doi: 10.1016/j.cageo.2012.07.021

Chilingarian, G.V., Rieke, H.H., Mazzullo, S.J., 1996. Introduction. In: Chilingarian, G.V., Mazzullo, S.J., Rieke, H.H. (Eds.), *Carbonate reservoir characterisation: a geologic-engineering analysis*, part II. Elsevier Science B.V., pp. 1-57.

Darbyshire, D.P.F., 1988. Geochronology of Malaysian Granites. *NERC Isotope Geological Report, British Geological Survey*, 3, 60 pp.

Deffontaines, B., Chotin, P., Ait Brahim, L. and Rozanov, M., 1992. Investigation of active faults in Morocco using mophometric methods and drainage pattern analysis. *Geol. Rundsch.*, vol. 81 (1), pp. 199-210.

DeFrates, J., Malone, D. H., and Craddock, J. P., 2006. Anisotropy of magnetic susceptibility (AMS) analysis of basalt dikes at Cathedral Cliffs, WY: implications for Heart Mountain faulting. *Journal of Structural Geology*, vol. 28, pp. 9–18.

Ellwood, B. B., 1978. Flow and emplacement direction determined for selected basaltic bodies using magnetic susceptibility anisotropy measurements. *Earth and Planetary Science Letters,* vol. 41, pp. 254–264.

Flugel, E., 2004. *Microfacies of Carbonate Rock: Analysis, Interpretation and Application.* Springer: New York.

Fontaine, H. & Amnan, I., 1995. Biostratigraphy of the Kinta Valley, Perak. Seminar on Permo-Triassic of Malaysia and associateed mineralization, April 14, 1994, Bangi, Selangor.

Foo, K.Y., 1990. Geology and Mineral Resources of the Taiping – Kuala Kangsar Area Perak Darul Ridzuan. *Geological Survey Malaysia, Map Report,* 1. Ipoh, Perak.

Gobbett, D. J., 1971. Joint Pattern and Faulting in Kinta, West Malaysia *Geol. Soc. Malaysia, Bulletin* No. 5, 39-48. Art Printing Works, KL.

Howard, A.D., 1967. Drainage Analysis in Geological Interpretation: A Summary. *The American Association of Petroleum Geologists Bulletin,* Vol. 51, No. 11, pp. 2246-2259.

Hutchison, C.S., 1968. Physical and Chemical Differentiation of West Malaysian Limestone Formations. *Geological Society of Malaysia Bulletin,* 1, 45-56.

Hutchison, C.S., 2005. The Geological Framework. In: Gupta, A. (Ed.), *The Physical Geography of Southeast Asia.* Oxford University Press, pp. 1-23.

Ibrahim Komoo, Ibrahim Abdullah, and Juhari Mat Akhir, 1989. *Teknik Pemetaan Geologi.* Penerbit Universiti Kebangsaan Malaysia, Bangi, Selangor.

Ingham, F.T., 1938. The Geology of the Neighbourhood of Tapah and Telok Ansan, Perak. *Geological Survey Memoir,* No. 2, Printers Ltd, Singapore.

Ingham, F. T. and Bradford, E.P., 1957a. Malaya Geological Series, 1:63,360, IPOH SHEET 2-N-5 & Part of 2-M-8. Geological Survey, Federation of Malaya.

Ingham, F. T. and Bradford, E.P., 1957b. Malaya Geological Series, 1:63,360, BATU GAJAH SHEET 2-N-9 & Part of 2-M-12. Geological Survey, Federation of Malaya.

Ingham, F. T. and Bradford, E.P., 1960. *Geology and Mineral Resources of the Kinta Valley, Perak.* Federation of Malaya Geological Survey District Memoir 9, Malaya: Goverment Press.

Jarvis A., H.I. Reuter, A. Nelson, E. Guevara, 2008. Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org.

Kobayashi, T., Burton, C.K., Tokuyama, A., and Yin, E.H., 1966. The Daonella and Halobia Facies of the Thai-Malay Peninsula Compared with those of Japan. In: Kobayashi, T. and Toriyama, R., (eds), *Geology and Palaeotology of Southeast Asia,* 3, pp. 98-122.

Krahenbuhl, R., 1991. Magmatism, tin mineralization and tectonics of the Main Range, Malaysia Peninsula: consequences for the plate tectonic model for Southeast Asia based on Rb-Sr, K-Ar and fission track data. *Geological Society of Malaysia Bulletin*, 29, pp. 1-100.

Lee, C.P., 2009. Palaeozoic Stratigraphy. In C. S. Hutchison and D. N. K., Tan (eds.), *Geology of Peninsular Malaysia*. Malaysia: University of Malaya and the Geological Society of Malaysia, pp. 55-86.

Liew, K.K., 1995a. Timing of Cenozoic basin formation in northern Sundaland, Southeast Asia. *Geological Society of Malaysia Bulletin*, vol. 37, pp. 231-251.

Liew, K.K., 1995b. Structural patterns within the Tertiary basement of the Strait of Malacca. Geological *Society of Malaysia Bulletin*, vol. 38, pp. 109-126.

Metcalfe, I., 1998. Palaeozoic and Mesozoic geological evolution of the SE Asian region; multidisciplinary constraints and implications for biogeography. In: Hall, R, Holloway, J.D. (Eds.), *Biogeography and Geological Evolution of SE Asia*. Backhuys Publishers, Amsterdam, The Netherlands, pp. 25-41.

Metcalfe, I., 2000. The Bentong-Raub suture zone. *Journal of Asian Earth Sciences*, vol. 18, pp.691-712.

Metcalfe, I., 1998. Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: the Korean Peninsula in context. *Gondwana Research*, vol. 9, pp. 24-46.

Metcalfe, I., 2011. Tectonic framework and Phanerozoic evolution of Sundaland. *Gondwana Reasearch*, vol. 19, pp. 3-21.

Metcalfe, I., Tectonic evolution of the Malay Peninsula. *Journal of Asian Earth Sciences* (2013). http://dx.doi.org/10.1016/j.jseaes.2012.12.011

Mitra, S., 1990. Fault-Propagation folds: Geometry, Kinematic Evolution, and Hydrocarbon Traps. *AAPG Bulletin*, vol. 74, pp. 921-945.

Nuraiteng Tee Abdullah, 2009. Mesozoic Stratigraphy. In: In C. S. Hutchison and D. N. K., Tan (eds.), *Geology of Peninsular Malaysia*. Malaysia: University of Malaya and the Geological Society of Malaysia, pp. 89-131.

Pierson, B. J., Kadir, A. A., Chow Weng Sum & Harith, Z. Z. T., 2009. Palaeozoic Hydrocarbon Plays in and Around Peninsular Malaysia: Any Chance of Exploration Success? *PETRONAS Technology Journal* vol. 2 (2), pp. 16-25.

Pubellier, M., Deffontaines, B., Quebral, R., Rangin, C., 1994. Drainage network analysis and tectonics of Mindanao, southern Philippines. *Geomophology*, vol. 9, pp. 325-342.

Ridd, M.F., A Middle Permian-Middle Triassic accretionary complex and a Late Triassic foredeep basin: Forerunners of an Indosinian (Late Triassic) thrust complex in the Thailand-Malaysia border area. *Journal of Asian Earth Sciences* (2012). http://dx.doi.org/10.1016/j.jseaes.2012.09.030

Savage, H.E.F., 1937. The Geology of the Neighbourhood of Sungei Siput, Perak. *Geological Survey Memoir*, No. 1, Printers Ltd, Singapore.

Suntharalingam, T., 1968. Upper Palaeozoic stratigraphy of the area west of Kampar, Perak. *Geological Socirty of Malaysia Bulletin*, vol 1, pp. 1-15.

Tjia, H.D. & Zaiton Harun, 1985. Regional structures of Peninsular Malaysia. *Sains Malaysiana*, 14(1), pp. 95-107. Earth Sciences.

Vahrenkamp, V.C., F., David, P., Duijndam, M., Newall, P., Crevello, 2004. Growth Architecture, Faulting, and Karstification of a Middle Miocene Carbonate Platform, Luconia Province, Offshore Sarawak, Malaysia, in *Seismic imaging of carbonate reservoirs and systems*: AAPG Memoir 81, pp. 329-350.

Walker, D., 1955. Studies in the Quarternary of the Malay Peninsula II: the Alluvial Deposits of Perak, and Changes in the Relative Levels of Land and Sea. *Journal Museums*, Federation of Malaya, Vol II.

Wang, B., Al-Aasm, I.S., 2002. Karst-controlled diagenesis and reservoir development: Example from the Ordovician main-reservoir carbonate rocks on the eastern margin of the Ordos basin, China. *AAPG Bulletin* 86, pp. 1639-1658.

APPENDIX: Lineaments of the granite

A. Kledang Range (No. of fractures: 156)

9	349	1	0	54	290	341	340	331	38
78	58	49	29	282	317	328	338	335	52
58	49	37	54	73	335	82	35	37	324
57	353	284	316	312	27	311	316	354	320
289	8	37	303	311	322	295	278	279	356
68	349	89	325	328	300	56	18	319	306
329	298	7	53	307	307	25	270	338	289
319	304	1	348	315	270	273	316	301	305
26	329	333	343	290	294	294	71	294	71
294	292	75	306	286	284	72	76	284	301
276	86	24	309	285	325	310	1	324	81
313	274	32	332	343	51	62	27	47	38
352	310	53	274	70	16	282	7	6	34
312	63	278	45	80	312	301	89	85	270
287	284	300	330	270	352				

B. Main Range – northern part (No. of fractures: 172)

314	338	330	67	327	306	305	343	333	303
315	309	333	350	296	14	313	74	60	328
35	328	308	35	328	310	18	78	19	25
22	306	310	36	314	342	299	35	314	5
325	351	290	343	331	357	316	297	352	318
290	337	334	17	317	83	273	333	10	82
291	317	341	306	316	300	301	314	311	323
299	327	320	340	359	0	358	14	14	357
8	12	9	349	305	6	358	4	14	310
304	18	311	28	290	56	340	42	271	300
342	4	352	20	315	352	53	316	273	337
321	311	86	271	347	11	286	9	77	324
72	279	24	10	17	18	67	305	302	305
71	332	326	311	62	352	2	39	16	321
299	318	290	271	65	3	66	355	6	83
305	335	327	339	12	339	332	306	11	57
4	321	57	66	32	347	334	340	286	314
352	295								

C. Main Range – middle part (No. of fractures: 236)

304	330	316	42	57	45	307	312	338	272
311	359	311	300	323	342	333	324	282	318
281	79	312	302	304	277	303	284	273	74
348	87	3	277	0	65	60	60	353	89
310	356	344	3	8	297	340	287	28	79
287	306	49	299	295	24	358	284	276	302
324	5	348	17	323	13	358	48	343	341
36	318	302	354	340	83	0	313	314	304
58	336	8	342	309	327	339	8	347	358
276	11	315	351	312	303	285	314	87	307
326	328	0	359	356	45	325	352	334	349
347	303	349	337	346	343	60	57	318	316
335	321	346	298	329	0	327	295	307	62
273	337	292	275	1	273	19	300	310	301
321	338	349	57	82	319	328	60	57	284
325	28	357	84	359	277	13	339	314	305
335	317	322	333	311	321	359	349	36	89
324	329	322	57	346	86	301	340	322	299
328	18	16	273	301	305	17	275	350	48
74	272	24	320	333	289	315	306	295	301
4	356	31	358	1	19	307	3	56	289
271	290	293	339	352	358	322	347	325	353
317	33	305	29	280	21	22	9	328	11
15	331	335	316	312	0				

D. Main Range – southern part (No. of fractures: 188)

308	42	11	312	301	270	89	62	336	7
3	356	7	8	333	313	0	345	324	21
339	359	343	11	42	304	64	338	288	323
322	358	43	28	348	70	79	305	302	303
0	85	11	29	1	6	302	306	79	290
303	84	356	3	84	344	323	284	8	4
1	282	354	283	276	83	281	358	333	354
302	7	2	352	7	284	69	342	88	352
0	19	20	332	291	17	319	351	298	306
79	318	299	359	292	32	323	319	324	310
87	297	339	318	285	285	329	348	334	276
312	294	292	311	272	356	279	345	333	279
9	281	4	344	357	270	271	0	300	301
299	281	358	351	325	343	349	274	39	5
301	306	306	356	320	302	305	292	313	310
77	299	309	76	283	296	319	303	322	315
332	344	283	299	305	292	333	83	278	320
338	331	89	307	299	289	76	278	284	318
338	318	311	296	310	7	352	280		