THE KINEMATIC STUDY OF THE BOK BAK FAULT ALONG KEDAH-PERAK TRANSECT

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FACULTY OF SCIENCE
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ABSTRACT

A section of Bok Bak Fault along southern Kedah and northern Perak is mapped for a detailed kinematic study of the fault. Remote sensing study shows a main NW-SE lineament crosscut by other lineament sets, and the lineament sets fit with a sinistral Riedel Shear model. The fault zone contain a main NW sinistral Bok Bak Fault set, with WNW sinistral set, NNW to NW sinistral set, NE dextral set, and E fractures. Mapping of mylonite along the fault zone reveals the presence of an early predominantly dextral strike slip movement along the shear zone. The shear zone is characterized by steep NW to W foliation with gentle to sub-horizontal NE stretching lineation deformed in the brittle-ductile domain. The shear zone is reactivated through sinistral to oblique slip movement, as shown by the overprinting of brittle faults and brittle-ductile shear zones on the mylonites. The Bok Bak Fault is reactivated as an oblique slip fault zone, resulting in crosscutting fault trend, which produce three main brittle episodes that are represented by NW and NNW faults, NE faults, and E faults. Brittle faulting is observed in both sedimentary rock unit and granite body. The faults are subsequently subjected to further reactivation, most likely during later extensional period along the fault zone, resulting in conflicting sense of movement along the fault trends. $^{40}Ar/^{39}Ar$ radiometric dating of biotite in mylonite produced a plateau age of 136.1 ± 1.4 Ma. This age is the first report of radiometric dating of the Bok Bak Fault, and here it is considered as the timing of the fault's initiation. The Early Cretaceous age achieved is later than the timing of initiation of regional fault discussed in other studies, where the faults of was previously thought to be formed concurrently with Late Triassic Main Range granite intrusion. Based on compilation of geochronological data, the Bok Bak Fault is interpreted to be initiated in Early Cretaceous, representing a major tectonic event in Sundaland prior to the collision of India and Asia, where the continental core became cratonized and major faults were being developed. This is a long lived event that

continued until Tertiary time, as evident from brittle reactivation along the fault zone. Recent reactivation of the fault is indicated by Quaternary sediment deformation and earthquake report along the fault zone.

ABSTRAK

Sebahagian daripada Sesar Bok Bak di sepanjang selatan Kedah dan utara Perak dipetakan untuk kajian terperinci kinematik sesar. Kajian penderiaan jarak jauh menunjukkan lineamen BL-TG dipotong oleh set lineamen lain, dan set lineament ini adalah serasi dengan dengan model Riedel Shear sinistral. Zon sesar mengandungi set utama BL-TG Sesar Bok Bak, dengan set mengiri BUB, set mengiri UUB ke BL set sinistral, set menganan TL, dan set rekahan T. Pemetaan milonit sepanjang zon kesalahan menunjukkan wujudnya akan pergerakan menganan awal sepanjang zon ricih. Zon ricih mempunyai foliasi BL ke B yang curam, dengan lineasi yang menjunam secara landai ke separa-mengufuk di dalam domain rapuh-mulur. Zon ricih diaktifkan semula melalui pergerakan mengiri ke pergerakan serong, seperti yang ditunjukkan oleh sesar rapuh dan zon ricih rapuh-mulur yang memotong milonit. Sesar Bok Bak diaktifkan semula sebagai zon sesar serong, seperti yang ditunjukkan oleh set-set sesar yang memotong set utama, denga tiga episod ricih yang menghasilkan sesar set BL dan UBL, TL, dan T. Sesar dapat diperhatikan dalam kedua-dua unit batu sedimen dan granit. Set-set sesar ini kemudiannya diaktifkan semula, pada tempoh pemanjangan (extensional) zon sesar, yang menghasilkan pergerakan yang bercanggah di sepanjang trend sesar. Penentuan umur radiometrik secara kaedah $^{40}Ar/^{39}Ar$ daripada biotit milonit memberi hasil umur 136.1 ± 1.4 Ma. Umur ini adalah laporan pertama penentuan umur radiometrik daripada Sesar Bok Bak, dan ia ditafsirkan sebagai umur permulaan pergerakan sesar tersebut. Usia Batu Kapur Awal yang didapati di dalam kajian ini adalah lewat dari masa pemulaan sesar rantau dibincangkan dalam kajian lain, di mana sesar-sesar sebelum ini ditafsirkan terbentuk serentak dengan penerobosan lewat granit Trias Banjaran Titiwangsa. Berdasarkan penyusunan data geokronologikal kajian terdahulu, Sesar Bok Bak ditafsirkan terbentuk ketika Batu Kapur Awal, yang

mewakili peristiwa tektonik utama di Sundaland sebelum perlanggaran India dan Asia, di mana teras benua mengalami kratonasi dan sesar-sesar utama dibentuk. Ini merupakan satu peristiwa tektonik yang berterusan sehingga Tertiari, seperti yang terbukti dari pengkaktifan rapuh sepanjang zon sesar. Pengaktifan semula sesar baru-baru ini ditunjukkan oleh canggaan sedimen Kuaterner dan laporan gempa bumi di sepanjang zon sesar.

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A shoutout for fellow postgraduate researchers – those who provided support throughout the period of my research, whether it was advising on my subject matter, or providing advices on researching and writing, or also burning the midnight oil on the sleepless nights where we're rushing for deadline.

Many thanks to Tuan Haji Zainol Haji Husin and the staff at JMG Kedah/Perlis/Pulau Pinang for providing access to materials during early stage of literature review for this work. Special mention goes to those who are of great help during my fieldworks: Encik Ismail Zainal Abiddin from Kuari Bina; Encik Jaafar from Kuari Pati; Encik Akok from Oscar Quarry; Encik Nizan from TAHB Quarry; Encik Shaari from Sankojaya Quarry; the rest of personnel in aforementioned quarries; and Aizad (who provided a place to stay during my fieldwork in Kuala Ketil and Baling).

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Lastly, and most importantly, I would like to dedicate this dissertation to my parents, Salmanfarsi Elias and Norliza Abu Bakar, who have been patient and supportive throughout my research.

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LIST OF SYMBOLS AND ABBREVIATIONS

Bt	:	Biotite
K-spar	:	K-feldspar
Ms	:	Muscovite
Plag	:	Plagioclase
Qtz	:	Quartz
BLG	:	Bulging
DEM	:	Digital elevation model
SGR	:	Subgrain
SRTM	:	Shuttle Radar Topography Mission

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

The Bok Bak Fault is one of the main fault zones of Peninsular Malaysia, stretching through the northwestern part of the Peninsula. It is rather extensive, with its trace starting from Perlis and extending southeastward through Kedah, Perak, and Kelantan. The Bok Bak Fault cuts through the Main Range Granite, as well as sedimentary rocks and their associated metasedimentary equivalent. The result of the faulting is expressed through topographic features and mesostructures in the field. The fault trace is well expressed in remote sensing imageries.

Although the Bok Bak Fault is a major fault zone, not many detailed study has been done on the fault zone as a whole: studies focus on small parts of the exposure of the faults, without much detailed study of the fault in a regional sense. Another notable observation is despite a large amount of igneous plutons being cut by the fault, most of the fault studies were focused on sedimentary rock formation. Compared to other well studied major faults of Peninsular Malaysia such as Bukit Tinggi and Kuala Lumpur Fault, the studies on the kinematic and mechanism of faulting is not well established. The work on deformed granite along the fault zone is lacking, which is to say that the deformation condition of the fault – in relation with the igneous intrusion of the region – is not known.

Of interest to this study are also recent evidences which challenge the claim of the Peninsula being a tectonically stable region: recent reports of earthquakes in Peninsular have led some researchers to consider faults which might have undergone reactivation in recent times, as a response to regional tectonic events. The Bok Bak Fault is among the structures that are prone to be affected by neighbouring tectonic events, and there have been several reports of recent seismicity near the fault zone which might be a result of the fault zone being reactivated.

This research will tackle the inadequacy of the studies related to the Bok Bak Fault by using new methods in an attempt to further understand the evolution of the fault zone.

1.1 Previous works

The Bok Bak Fault was first described by Burton (1965), where he mapped a 51 miles extension of the fault in the Baling-Jeneri area based from the study of aerial photographs and field check. The LANDSAT lineament study of the Bok Bak Fault (Raj, 1982) further extend the fault southward to central Perak and southwest Kelantan, based on the apparent displacement of Paleozoic sedimentary formation in Perak and the offsetting of the Main Range granite in Perak. The northwestern extension of the fault from Pokok Sena to Wang Kelian was proposed based on the drag of strike ridges, displacement of Paleozoic formations, and features such as deflected rivers and hot springs along the fault zone (Syed, 1996).

Field occurrences of shear zones in sedimentary formation (Jones, 1970) and granite (Jones, 1970; Abdul Majid, 1987) in the proposed extension of the fault were seen as being clear indicator of the existence of the Bok Bak fault further southeast from Baling. Subsequent field study in central and northern Kedah have reported on the occurrence of the fault in sedimentary formation (Mustaffa, 1994; Zaiton and Basir, 1999) and granite body (Abdullah, 1993). A gravity survey of Perlis, Kedah and Penang have detected trace of the fault underneath the sediment cover, and the displacement along the fault was also identified (Burley and Jamaluddin, 1990).

Several studies have been done on the deformation in sedimentary formations affected by the Bok Bak fault, especially those that are of the Mahang Formation and Semanggol Formation in northern and central Kedah (Ibrahim et al., 1989; Zaiton and

Basir, 1999; Zaiton et al., 2009). The fault was believed to result in transpressive regime, resulting in folding and reverse faulting adjacent to the fault (Zaiton and Basir, 1999, 2000).

Zaiton (2002) have studied the timing of deformation for the ductile deformation of Bukit Tinggi and Bukit Berapit Fault, but have not noted a similar occurrence in the Bok Bak Fault. The report of ductile mylonite with sinistral shearing in Bukit Perak (Abdullah, 1993), and the discovery of linear drainage system, quartz reef, outcrops of mylonites, cataclasite and shear zones in Sungai Siput area, north Perak (Abdul Majid, 1987), points to early ductile deformation of the Bok Bak Fault.

Majority of the previous works on the Bok Bak Fault are focused on the effect of faulting on sedimentary rock unit, with little detailed studies on the effect of faulting on granitic bodies. As such, the kinematic and deformation history of the fault is still not fully understood.

1.2 Objectives of study

The lack of detailed works on the early ductile deformation of the Bok Bak Fault would point out that the condition of deformation and kinematic history of the fault were not fully studied. A more detailed kinematic history of the fault and its relationship with other fault system of the Peninsula is important in delineating the role of the fault in the tectonic history of the region. The research focus on these main objectives:

To characterize the distribution and trend of the Bok Bak fault zone

The extent and trend of the structures along and outside of the research area was studied to delineate the whole Bok Bak Fault system. This also include other secondary faults along the main fault zone. Since the fault zones are composed of various intersecting faults sets, various faults of differing trends found in the field was described and characterized.

To determine the kinematics and condition of deformation of the fault zone

The sense of movement during the faulting is interpreted from kinematic studies from the field and examination of fault rocks. Information on the temperature, pressure, and depth of the fault was studied based on microstructure of the fault rocks.

To discuss the implications of the deformation of Bok Bak fault system on the different phases of the tectonic evolution of Peninsular Malaysia

The history of deformations along the fault zone was studied in relation to the different stages of the tectonic evolution of the Peninsula, which results in various structural trends found in the region.

To determine the deformation history of the fault zone and to interpret the implications of the deformation history along the regional tectonics

Different phases of deformation along the fault zone will result in differences in the generation of faults and other geological structures. These structures were studied, as well as the timing of the deformation phases which result in the structures. The timing of deformation phases was sought from relative and radiometric dating, to interpret the regional tectonics.

1.3 Methodology

The study combines lineament analysis, detailed field mapping, and petrographic and microstructural study of oriented sample. A simplified progress of the research is summarized in a flow chart form (Figure 1.1).

1.3.1 Desk study

The early work of the research focuses on examining available maps and satellite image to identify accessible outcrops. Published map and geologic report along the research area was studied to get the general geology of the area. Other relevant literatures related to the topic are also examined.

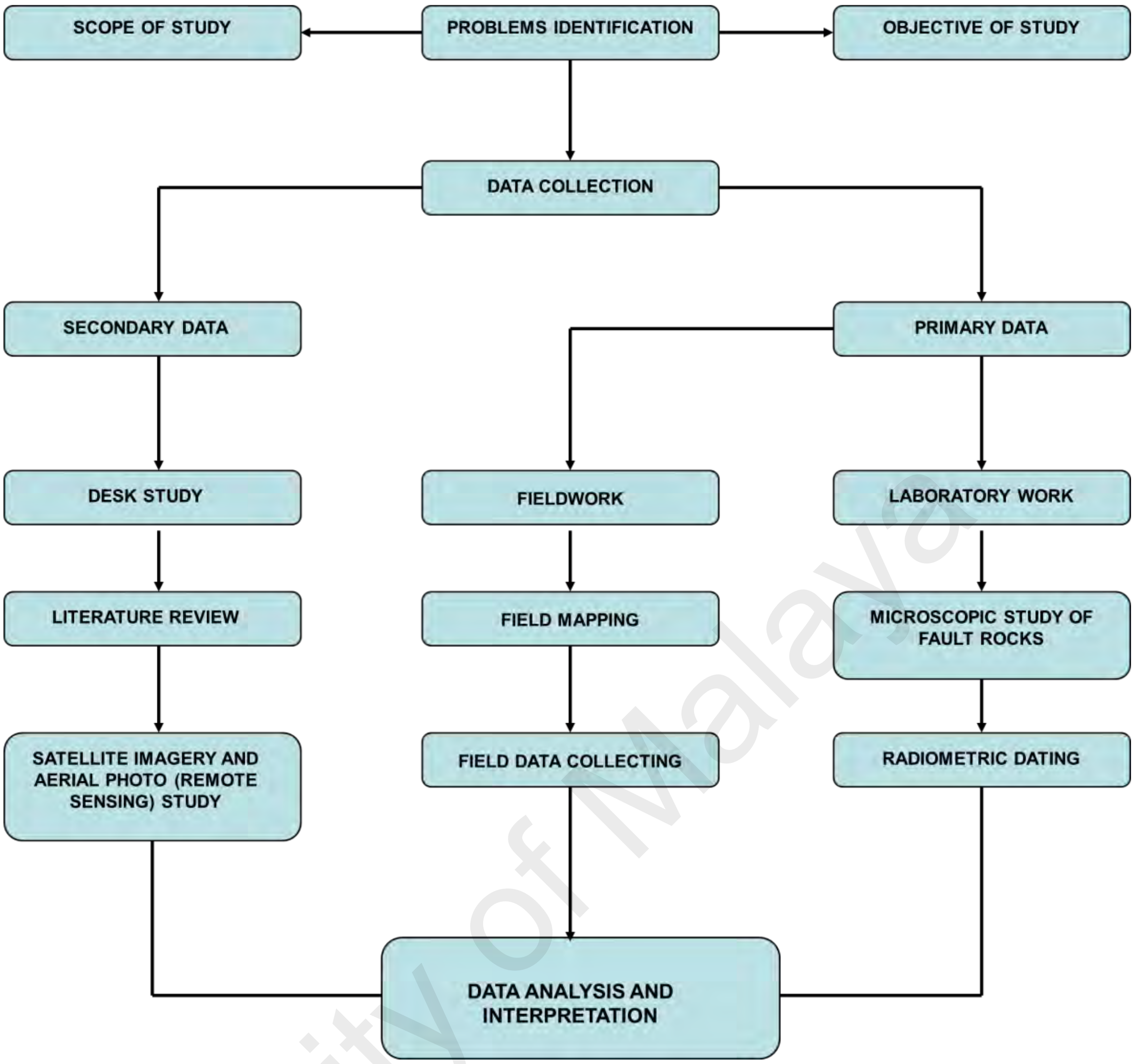

Figure 1.1: Flow chart of research progress

1.3.2 Remote sensing

The study of Digital Elevation Model-Shuttle Radar Topographic Mission (DEM-SRTM), LANDSAT satellite images and 1:25000 aerial photographs_was carried out to delineate the distribution, trend, and extension of the Bok Bak fault and its subsidiary faults. Over these methods, the DEM-SRTM provides the best method in extracting and analyzing lineament pattern. All these methods are combined to get the most accurate lineament extraction of the study area. The result of the lineament study is presented in subsequent chapter on the Bok Bak Fault (Chapter 3). The steps for lineament extraction are as follow:

1.3.2.1 Aerial photographs

Several sets of aerial photographs at the scale of 1:25000 of area in Bukit Perak, Bukit Enggang, and Baling were studied. By using stereoscope, lineaments were sketched on tracing paper, which were then transferred to topographic maps scale of 1:50000. Lineaments are identified from long and straight topographic features shown in the three-dimensional view.

1.3.2.2 Satellite imageries

LANDSAT image sets were used, with two sets studied: a year 1990 image with 28m resolution, and a year 2000 image with 14.5m resolution. Both satellite images are in UTM Zone 47 projection. Lineaments are identified in the images as long and straight feature, although attention is given to distinguish natural and man-made linear structure. Two set of images are used due to the effect of cloud coverage in the year 2000 image. The plotting of the lineament is done entirely manually over the images.

1.3.2.3 DEM-SRTM

Digital Elevation Model-Shuttle Radar Topographic Mission (DEM-SRTM) is primarily used for lineament extraction, where the lineaments were extracted manually. Although there are several methods for automated extraction of lineaments from DEM, the lineaments here were plotted manually through ArcMap software. Shaded relief images were created from DEM to accurately pinpoint the lineaments. The DEM were processed so that shaded relief images were produced from various illumination conditions: lighting azimuth of 0°, 45°, and 90° were applied to prevent bias of lineament picking.

1.3.3 Field work

Geological mapping was carried out to differentiate the different lithology unit, particularly the granite and sedimentary rock. Faults and shear zones in the field were studied, with their planar and linear features recorded. Other related structures to the fault such as joints, veins, dikes, and folds were also studied. The mapping was facilated by the use of Global Positioning System (GPS) in locating outcrops and facilitating navigation, and the ArcGis software was used to analyze field data and compile the final geologic map.

Where possible, fault rocks samples were collected for microstructural and radiometric study. The kinematic of the faults were studied based on mesoscopic observation as well as microstructural study.

1.3.4 Laboratory work

Samples brought from the field was processed at the laboratory for the petrographic and geochronological study on the fault rocks:

Petrographic study of fault rocks

Petrography of undeformed granite and deformed granite was studied from prepared thin sections. For deformed rocks, oriented thin sections were prepared, and the analysis of the microstuctures of the deformed rocks would discern the sense of fault movement.

Geochronology

Samples were sent to the Activation Laboratories Ltd. (Actlabs) in Canada for the dating of deformation during faulting event through $^{40}Ar/^{39}Ar$ dating method. The argon in the secondary biotite of the faulted rocks was dated by using the method

1.4 Study area

For the purpose of the study, the areas covered are portion of central and southeastern Kedah, with a small part of northern Perak (Figure 1.2). The area was chosen based on the availability of exposed granite at quarries of Bukit Perak and Bukit Enggang, the large area of exposed sedimentary formation in Kuala Ketil, and exposed sheared granite along Baling-Gerik road – all which are along the trace of the fault.

Previous works were studied beforehand to facilitate a plan to collect data from unobserved area around the fault trace, or to conduct more detailed data collection where necessary.

The north part of the study area starts near Sungai Tiang, where several active granite quarries of Bukit Perak (Bina Quarry, Pati Quarry, Oscar Quarry) are to be found. The granite quarries were found on the west side of the granite massif along Sungai Tiang

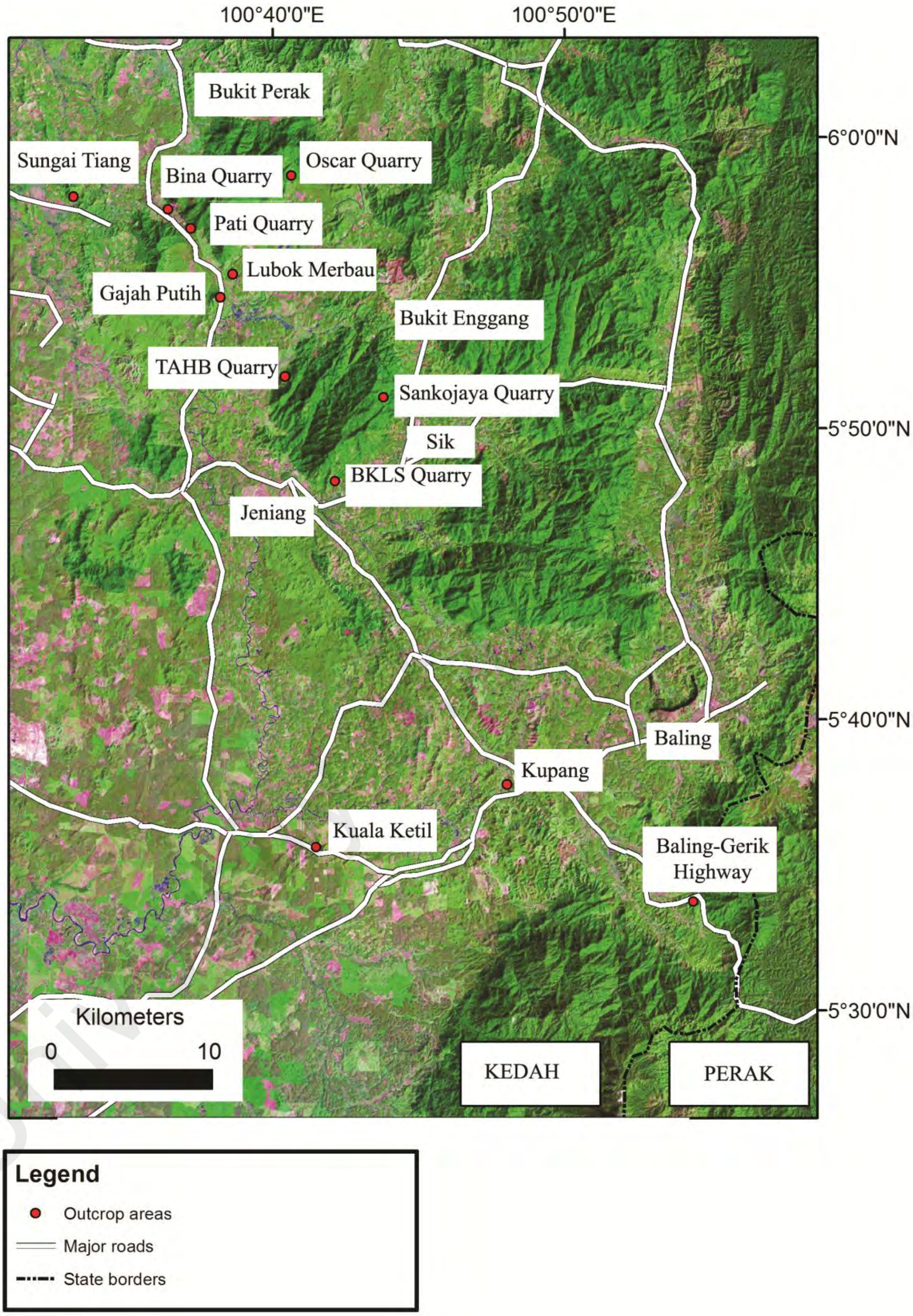

Figure 1.2: Location map of study area, with outcrops, towns, and roads labeled. Base map used is LANDSAT image, year 1990, with 28m resolution.

area, and further northeast near Lubok Merbau. Further southeastward along the study area are the quarries of Bukit Enggang (TAHB Quarry, BKLS Quarry, Sankojaya Quarry). In both areas the granites are found in rural areas, with moderate to good accessibility through the main road and smaller roads.

Further south in Kuala Ketil, the sedimentary rocks were well exposed along roadcuts and hillcuts. The area lie in between township of Kuala Ketil to west and Kupang in the east, with the east-west road connecting Sungai Petani-Baling providing some rather well exposed outcrops. At the furthest southeastern part of the study area are granite exposure along Baling-Gerik highway. The mapped area along the highway extends slightly further from the Sungai Rui area, at the Kedah-Perak boundary.

1.5 Physiography

The landscape of the area is characterized by hills and valleys, with several granite bodies forming highland areas (Figure 1.3). The two main granite pluton of Bukit Perak and Bukit Enggang show up distinctly in topographic map and satellite imageries, while the portion of the Bintang Range granite crops up as highland at the southern part of the area amidst the hilly topography around Baling.

Besides the highland and flat plain, one the most striking geomorphological feature that can be found is the occurrence of strike ridges: linear positive relief features which could readily be viewed from satellite imageries. These structures are found in the Kubang Pasu and Semanggol Formation rocks, and correspond with the general strike trend of the sedimentary beds in the area. These structures are especially well observed in Kuala Ketil.

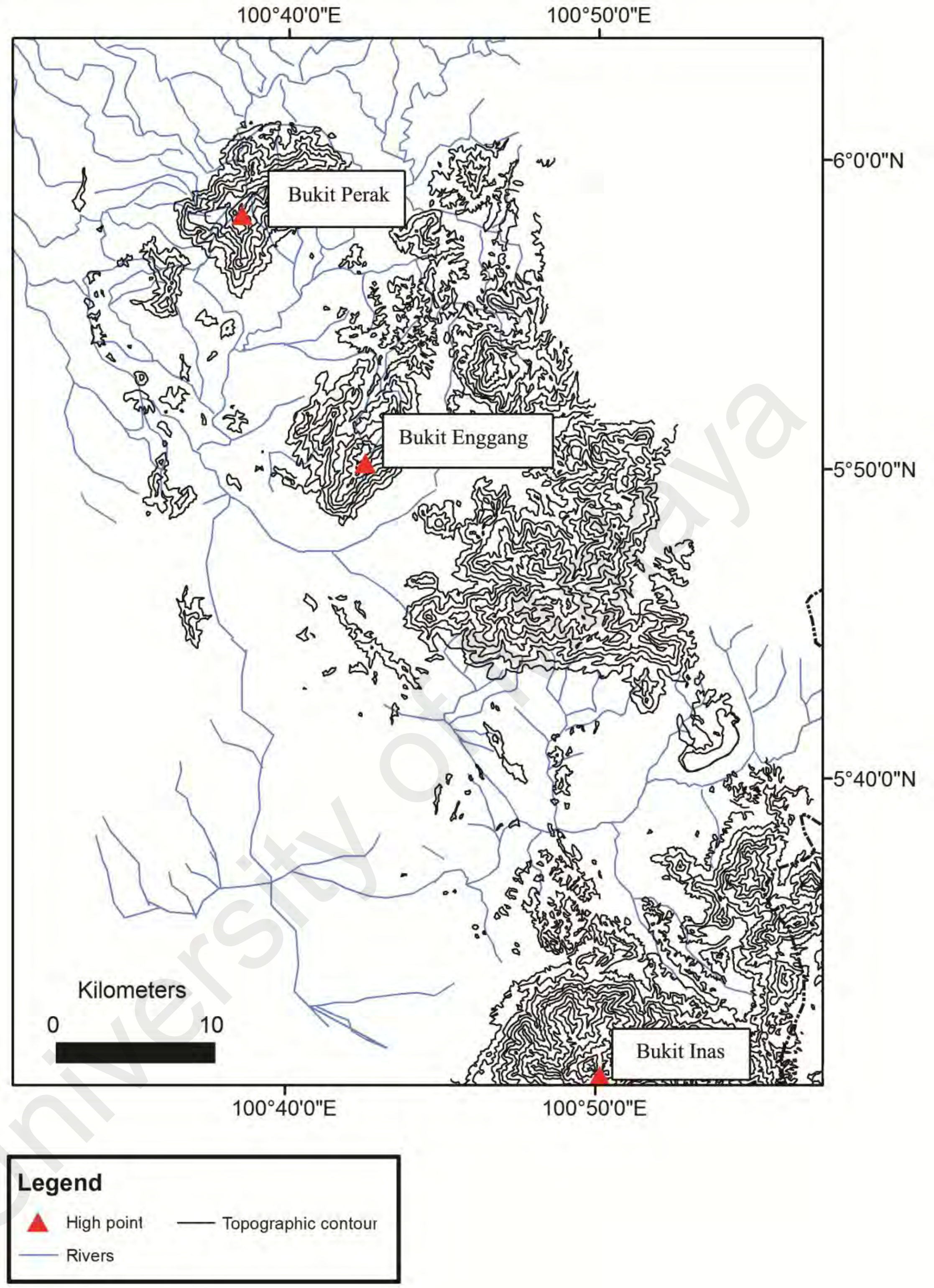

Figure 1.3: Topography of study area, with main rivers plotted. Triangle symbol refers to highest point of granite bodies. Topographic contour interval is 100 m.

In general the topography and drainage pattern in the area appear to be controlled by the lithology and structure, with different geology producing some decidedly distinct topographic feature.

1.5.1 Topography

In Bukit Perak area, the northwest of the granite pluton is relatively flat and low lying. Closer to the granite pluton, several north-south trending strike ridges break the monotony of the flat area. The Bukit Perak granite pluton appear as a large rectangular block which trend NE-SW, with remarkably straight and steep slope in contact with the low lying sediment. The highest point on the granite pluton is Bukit Perak (865 m).

The Sungai Muda Valley forms as a low lying area between the Bukit Perak and Bukit Enggang granite pluton. The valley was believed to be underlain by the conjugate fault set that cut the Bok Bak fault, which was named the Muda Valley Fault (Burton, 1965) and the Lubok Merbau Fault (Abdullah, 1993). Further south, the topography of the area is more hilly. The Bukit Enggang granite pluton crops up as an oval-shaped structure, trending roughly at NE-SW. Bukit Enggang (772 m) is the highest point of the granite pluton.

In Kuala Ketil, the most notable topographic feature are the occurrence of long parallel sets of ridges (Figure 1.3). These features are well observed in topographic map and remote sensing. At the west, near the town of Kuala Ketil these ridges trend at a northeast-southwest trend. Further eastward towards Kupang and Baling, the ridges swerve to a NNE-SSW trend as they approach the trace of the Bok Bak fault. Further east of the Bok Bak fault trace, the limestone hill of Baling forms a highland with a curved shape that follows the valley around it.

Southward near the end of the study area lies the granite of the Bintang Range. The most notable high point of the granite here is Bukit Inas, situated at the north end of the Bintang Range. The slope of the hill descend sharply into the valley of Sungai Ketil. Burton (1970) had pointed out that the Bintang Range granite could be found to extend further northeast of Kedah into Thailand.

1.5.2 Drainage pattern

In both the Bukit Perak and Bukit Enggang pluton, the rivers show a predominantly dendritic pattern in the pluton (Figure 1.4). As the plutons have steep gradient, the rivers are fast flowing, and waterfalls could be found. Around the pluton, the rivers show a predominantly northeasterly-southwesterly direction through the flat and valley area. Several of the main rivers include Sungai Jeneri (flowing from east to west) and Sungai Muda northeast to southwest). Sungai Muda and other branching river flows southwestward through the Muda Valley.

Further south, the main river is Sungai Kuala Ketil, where it flows in a southwesterly manner through Kupang and Kuala Ketil area. The river corresponds to the general strike of the underlying sedimentary beds, and as such could be described as a strike stream. At Baling, the river direction swerves to form a southern-southeasterly flow direction. South of Kupang, the river branch off southeastward, which forms the two main set of river: Sungai Kupang and Sungai Tiak. Both rivers flank Kampung Bok Bak, flowing in the valley adjacent to the Bintang Range granite pluton.

The drainage pattern appears to be affected by the underlying geology and structure. In sedimentary formation, the river could be found to correspond to the strike trend of the sedimentary formation. The dendritic river pattern on the granite plutons are

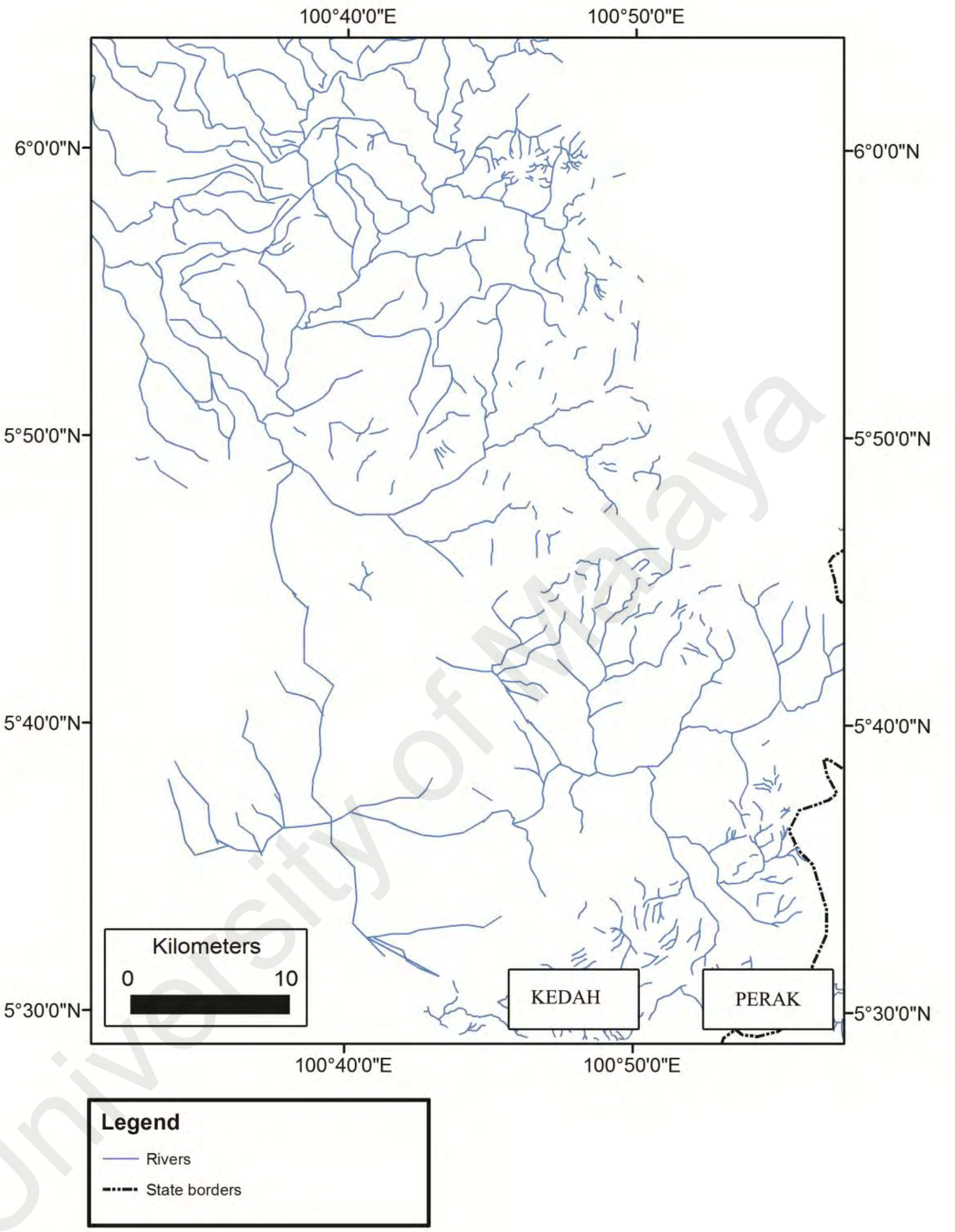

Figure 1.4: Drainage map of study area

possibly controlled by cooling joints formed after the granite emplacement. Several of the river flow seems to be fault controlled: this is suggested by their linear pattern and their trend which coincide with the major trend of the faults. These rivers are more pronounced in granite pluton, where the fault cutting the granitic bodies result in more pronounced lineaments. In sedimentary formation, presence of bedding makes it difficult to differentiate between the structural control of faults or bedding discontinuities. This is especially obvious in Baling where both the river and structural trend swerve in a direction similar to the Bok Bak fault.

CHAPTER 2: REGIONAL SETTING AND GEOLOGY OF BOK BAK FAULT ZONE

2.1 Regional tectonic setting

The Peninsular Malaysia forms part of the regional block of Sundaland, a South East Asian part of the Eurasian Plate (Hutchison, 2007, Metcalfe, 2011). The term strictly defines the landmass of South-East Asia which include Sumatra, Java, and Borneo which stood above sea level during the low sea level of Pleistocene epoch (Voris, 2000), but it is acceptably used in referring a South-East Asian continental part of the Eurasian plate (Hutchison, 2007).

The continental core of Sundaland consist of the South China block, the Indochina block, the Sibumasu terrane, West Burma block, West Sumatra block, and SW Borneo block (Figure 2.1). The margin of Sundaland is defined by Sagaing-Namyin Fault in the west, extending southward into the Andaman Sea and west of Sumatra. The margin of Sundaland in the east is more fragmented and complicated due to the opening of Tertiary basins and occurrence suture zones. Most of the continental blocks of SE Asia were derived from the southern hemisphere of the supercontinent Gondwana (Metcalfe, 1988), and were progressively assembled during Late Palaeozoic to Cenozoic convergent tectonics, leading to the present continuous collision of India and Asia, and Australia with SE Asia (Morley, 2012).

The convergence between the Indian and Asian plate is an important event in the tectonic evolution of SE Asia. The models by Tapponnier et al. (1982, 1986) have shown that the faults feature of SE Asia could be produced by the collision of India and

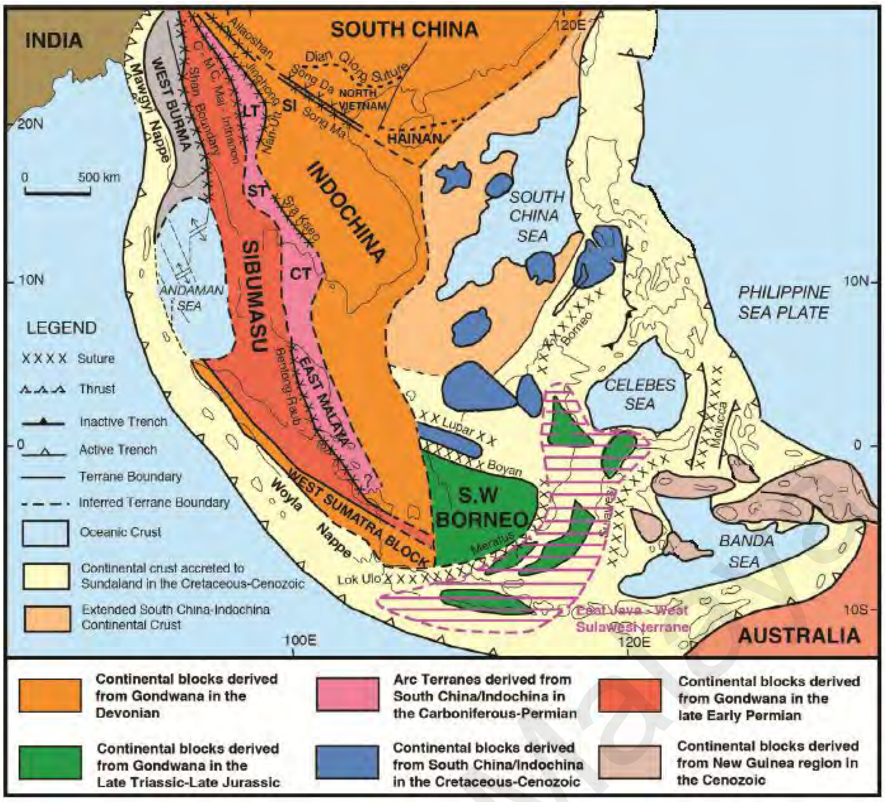

Figure 2.1: The continental core of Sundaland (modified from Metcalfe, 2013)

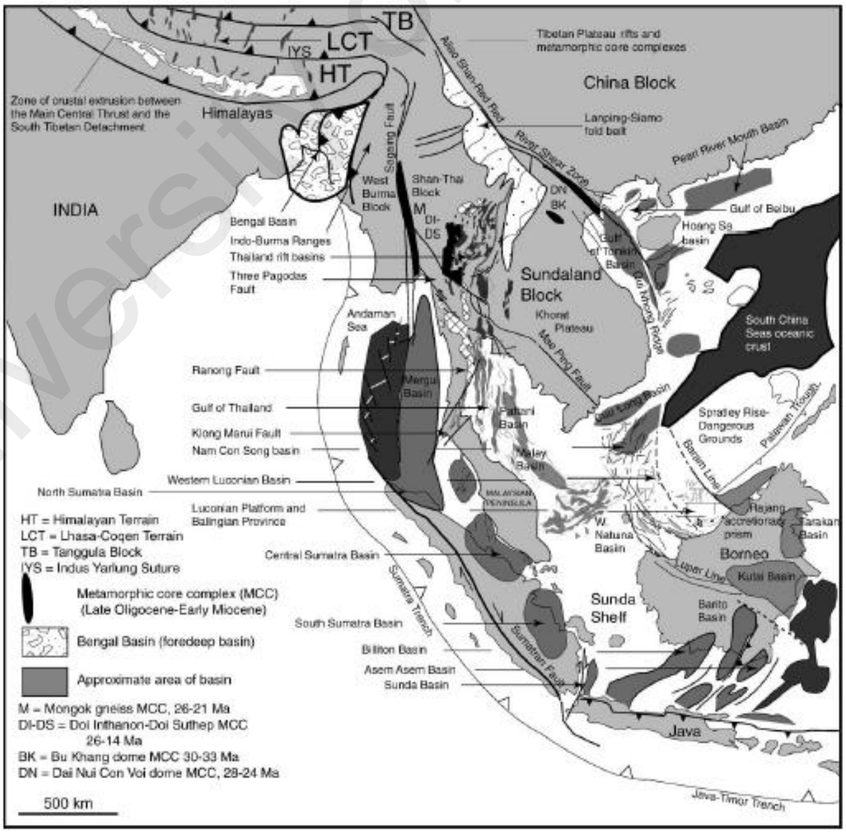

Figure 2.2: Tectonic and structural features of SE Asia (Morley, 2002)

Eurasia through extrusion tectonic. Subsequent studies have discussed on the model of escape tectonic and its relationship with the major faults and Cenozoic basins of SE Asia (e.g. Morley, 2002). Most of these faults are right-lateral wrench faults, resulting from clockwise rotations (Hutchison, 2007) (Figure 2.2).

2.2 Geological setting of Peninsular Malaysia

The Peninsula hosts an array of geology, subjected to regional tectonic forces which produce the multitude of structural styles observed in the present. Various works by geologists incorporating these diverse rock assembly observed with various proposed tectonic models have resulted in the general subdivision of the Peninsula into three belts: the Western Belt, Central Belt, and Eastern Belt (Figure 2.3). This subdivision resulted from the development of the study which distinguishes different stratigraphy, structure, magmatism, geophysical signatures, and geological evolution between these belts (Metcalfe, 2013).

Two main tectonic blocks forms the Peninsular Malaysia: the Sibumasu Terrane and East Malaya Block (Figure 2.1). The Western Belt is part of the Sibumasu Terrane, whereas the East Malaya Block consists of the Central and Eastern Belts. Recent works have identified a volcanic arc terrane, the Sukhothai Arc, in the western margin of Indochina-East Malaya block (Sone and Metcalfe, 2008).

The study area falls under the northwestern domain of the western belt of the Peninsular, an arbitrary subdivision of the Western Belt of the Peninsula. This subdivision is based on the most complete Paleozoic rocks exposure, from the age of Upper Cambrian to Upper Permian (Lee, 2009). The geology of the area is dominated

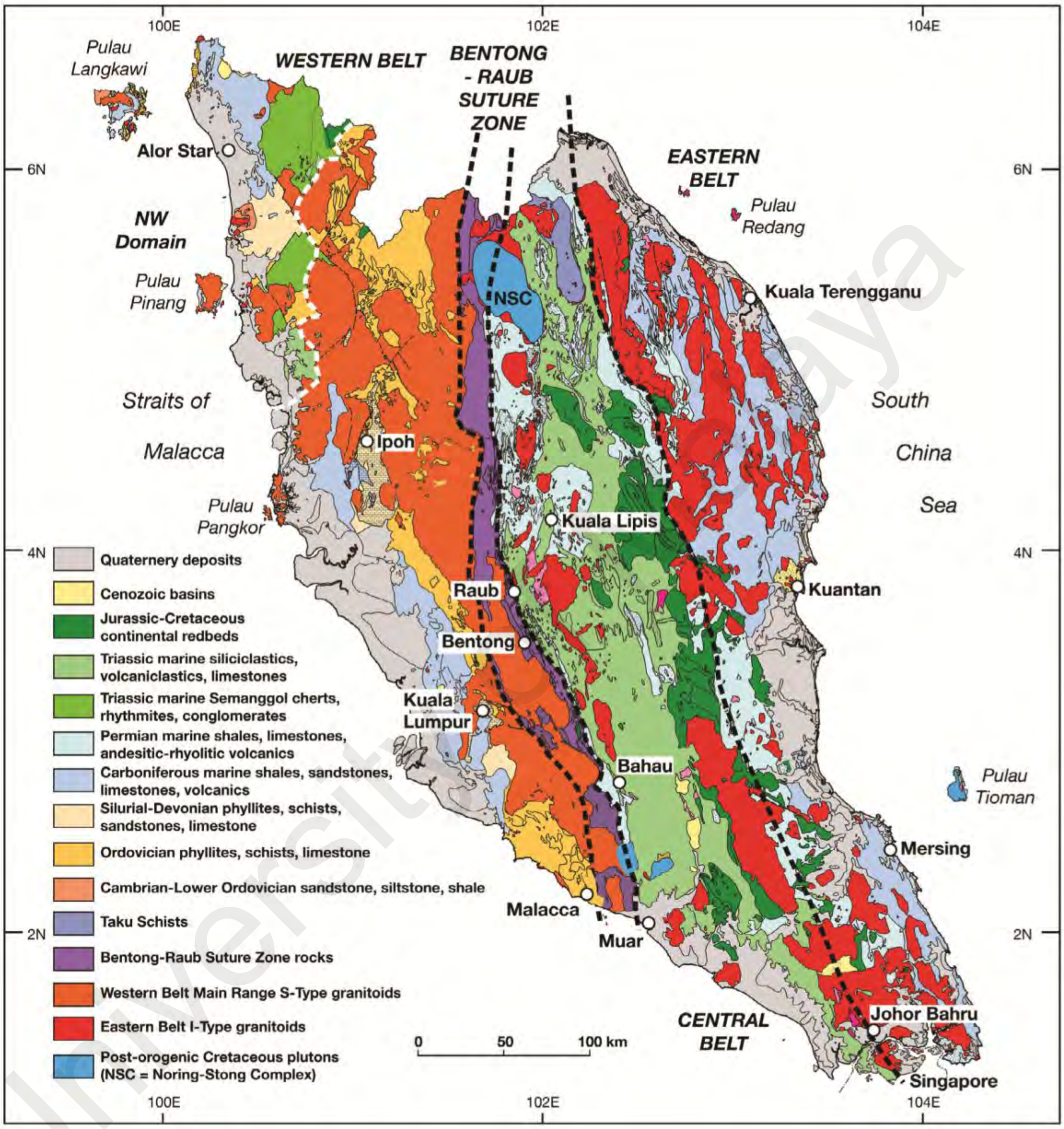

Figure 2.3: Simplified geology of Peninsular Malaysia, with the geological belts and Bentong-Raub Suture Zone illustrated (Metcalfe, 2013)

by Paleozoic and Mesozoic aged sedimentary rocks with occurrence of granite plutons. The Bok Bak Fault is a major fault that cut across the lithology.

The geological belts are also separated by structural elements: the Bentong –Raub Suture Zone separates the Western and Central Belt, while the Central and Eastern Belt is marked by the Lebir Fault Zone (Figure 2.4). The boundaries between the Northwestern Domain with the Western Belt is however unclear, as no major structure separate within the western belt.

2.3 Fault system of Peninsular Malaysia

The Peninsular is transected by several sets of major strike slip faults. These faults came to be recognized from earlier studies of remote sensing and field mappings, with new faults subsequently discovered through study of satellite imageries and shuttle radar imageries.

The faults can be seperated into three categories based on their orientation and position to the terranes of Peninsula: terrane-bounding faults, terrane-parallel faults and terrane-cutting faults (Mustaffa, 2009a). The Bok Bak Fault belong in a group of NNW-SSE and NW-SE terrane-cutting faults, which includes other faults such as the Bukit Tinggi, Ruok, Galas, Lebir, Lepar, and Mersing fault zones. Figure 2.5 show the distribution of these faults in relation with the fault system of Peninsular Malaysia.

The NNW-SSE to N-S faults were believed to be initiated as dextral strike-slip faults after the amalgamation of the two tectonic blocks of the Peninsula during Permian to Triassic time, after or during the late stage of the emplacement of the Main Range Granite during late Triassic to Jurassic (Mustaffa, 2009a). An isotope dating by Zaiton

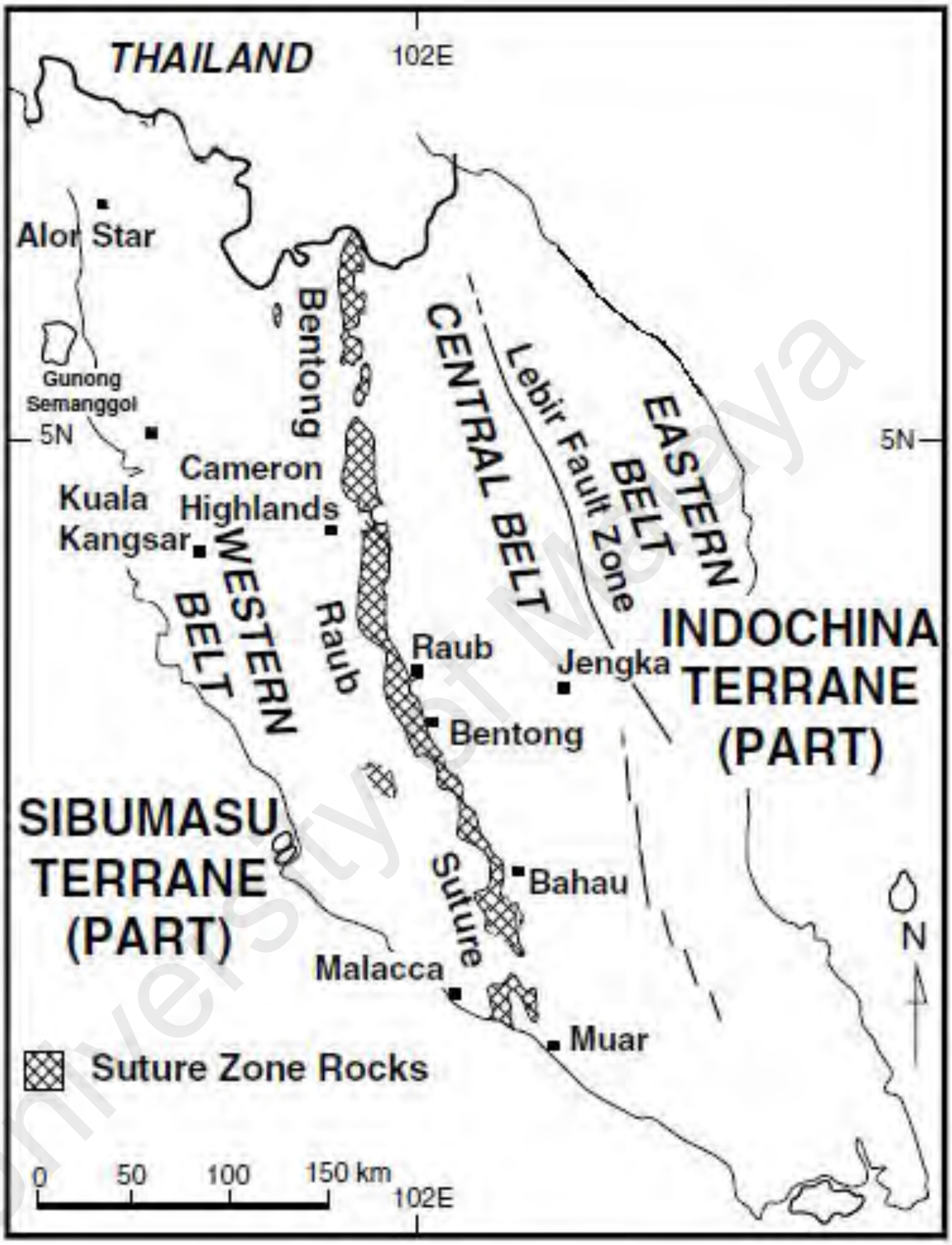

Figure 2.4: The three geological belts of Peninsular Malaysia separated by the Bentong Raub Suture and Lebir Fault Zone (Metcalfe, 2000)

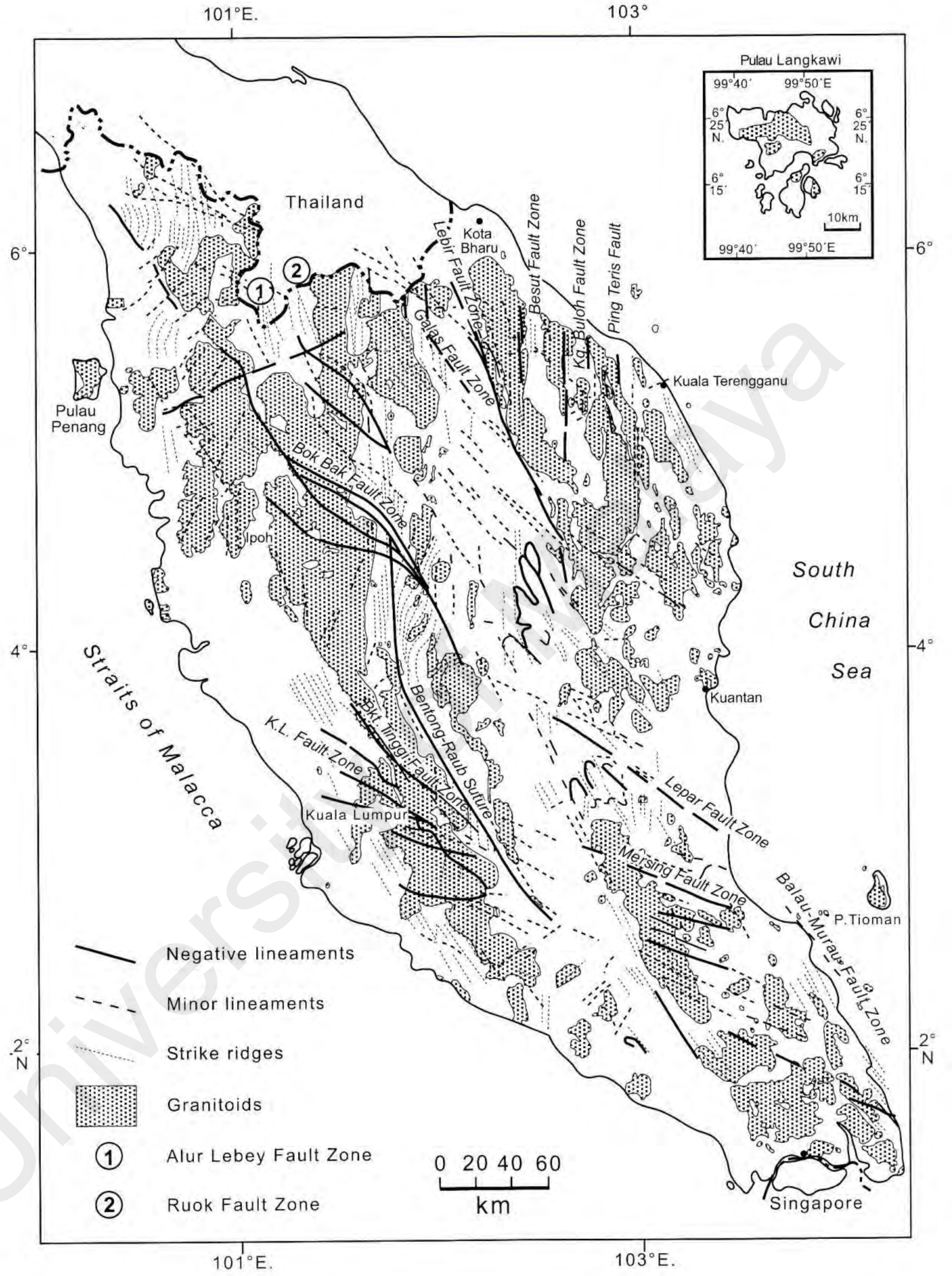

Figure 2.5: Major faults of Peninsular Malaysia (Mustaffa, 2009a)

(2002) on mylonite from NNW-SSE Bukit Tinggi fault result in late Cretaceous age: it was believed that movement of the NNW-SSE, NW-SE and WNW-ESE strike slip fault was sinistral during this time period, and movement of the Bok Bak Fault during this period result in transpressive deformation of sedimentary formation adjacent to the fault (Zaiton, 1993; Zaiton and Basir, 1999, 2000). These sinistral movements could thus be taken to represent reactivation along the previously dextral strike slip faults, as there are reports of both dextral and sinistral microstructure in the fault zone (e.g Ng, 1994; Zaiton, 2002). The report of the occurrence of both dextral and sinistral movement along these faults suggested that the faults are subjected reactivation from a ductile deformation to a brittle deformation (Ng, 1994). Mustaffa (2009a) had suggested the earlier dextral ductile deformation of Bukit Tinggi Fault might have taken place during Late Triassic – Jurassic, after or at least at the late stage of Main Range Granite emplacement.

The Tertiary basins along trace of NW-SE faults were reported to be formed during reactivation of the faults in Tertiary (Raj et al., 1998, Zaiton, 2002). The India-Eurasia collision has resulted in reactivation of pre-existing structures in the region, where it was suggested that the escape tectonics utilized pre-existing zone of weaknesses such as suture zones and previously formed shear zones (Hutchison, 2007). Metcalfe (2013) have however pointed out the finding of counter-clockwise rotation of Peninsular Malaysia during Cenozoic time (Richter et al., 1999), which would be incompatible with the ‘extrusion model’ of the India-Eurasia collision.

2.4 Rock units of the Bok Bak Fault Zone

2.4.1 Sedimentary formation

The central and southern Kedah is covered extensively by sedimentary formation, neighboured by bodies of granitic intrusions. The sedimentary formation forms the majority of low lying area, as well as several of the hills and set of parallel strike ridges. The Bok Bak Fault is seen acting as forming a separation between these two lithology.

In the north of the study area, the Mahang Formation occurs adjacent to the granite plutons of Bukit Perak and Bukit Enggang. The Semanggol Formation are found further northward from these granite plutons. Further south, the Semanggol Formation covers majority of the area, stretching from Kuala Ketil until Baling. The granite of the Bintang Range crops up further south, separated from the nearby sedimentary formation by the Bok Bak Fault. The Baling Formation rocks are found in close proximity to the granite, producing a host of metasedimentary product from the original sedimentary rocks.

2.4.1.1 Baling Formation

The Baling Formation (earlier classified as the Baling Group) is employed by Burton (1970) to describe the large occurrence of metamorphosed sedimentary sequence within the area of Baling. He identified four main facies of arenaceous, argillaceous, calc-silicate and limestone. The facies of the formation are of lenticular nature, each having interfingering contact with one another: as such the actual contact between the different facies are difficult to be pointed out exactly. The limestone forms several of the prominent hills in the area, with the notable horseshoe shaped hill in west Baling. Trace of the Baling Formation could be found further south in Grik, where it occurs

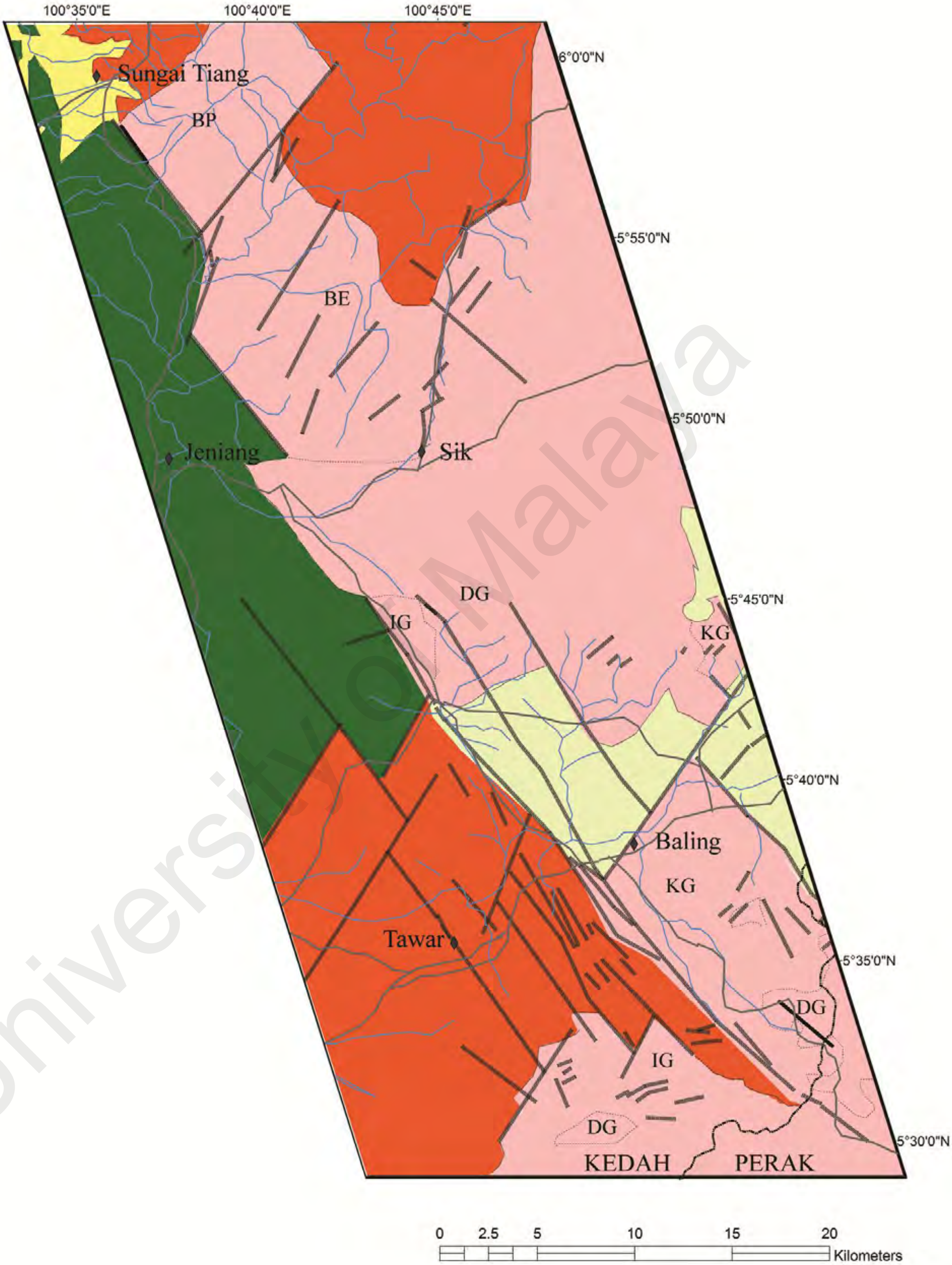

Figure 2.6: Geological map of study area (geology from field mapping, and modified from Burton, 1970; and Teoh, 1992).

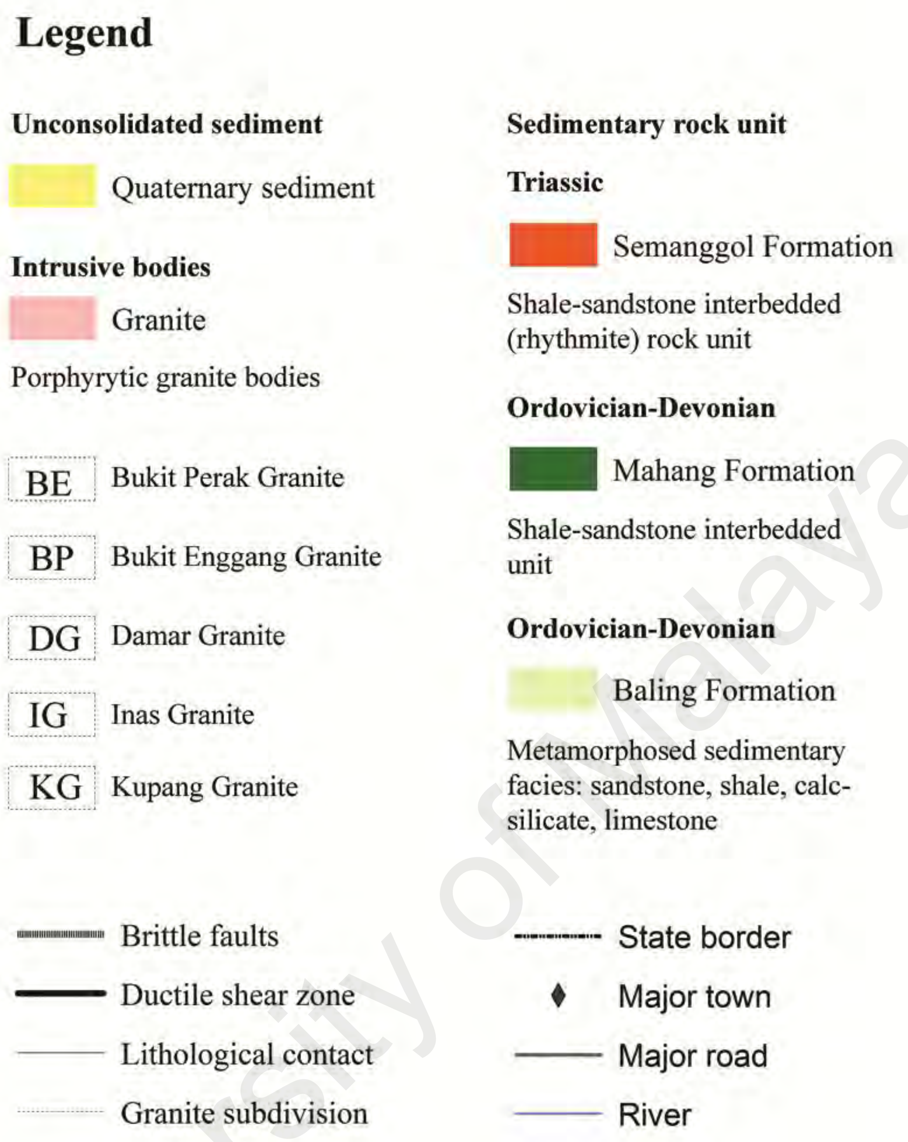

Figure 2.6, continued

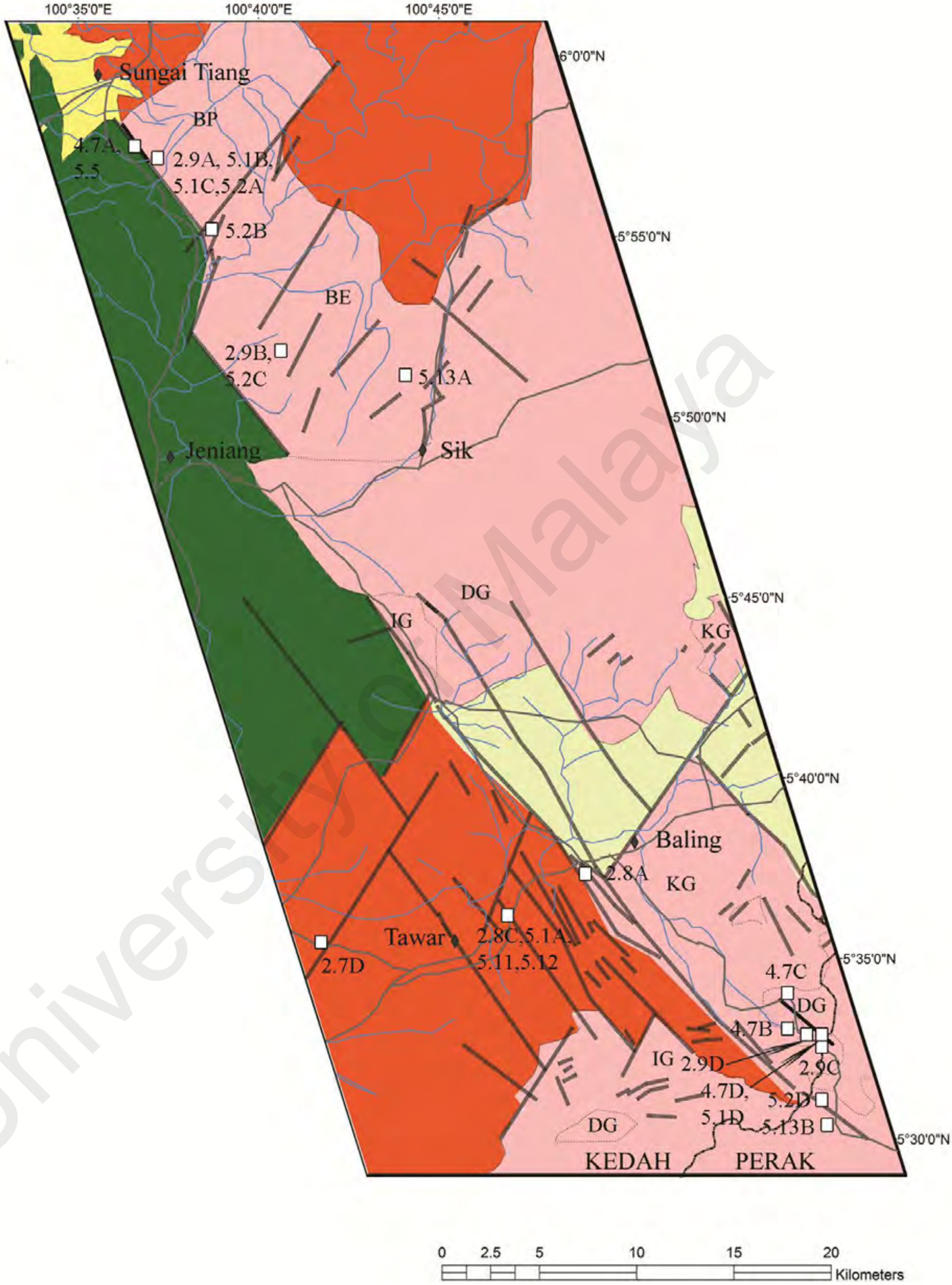

Figure 2.7: Locations for mapped field photos in the study (squares). Refer to Figure 2.6 for details on legend of map.

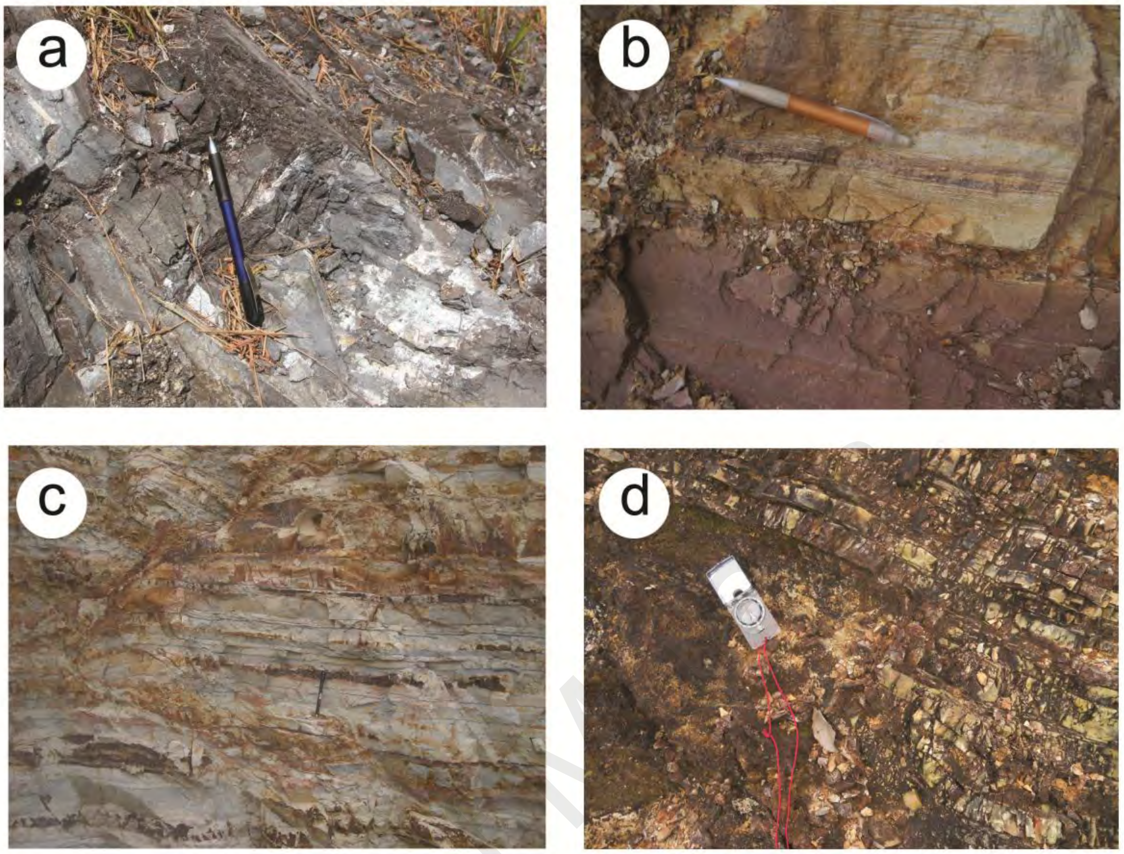

Figure 2.8: Sedimentary rock of the study area: a) Argillaceous rock unit of Baling Formation. Location: Kupang; b) Reddish shale of Mahang Formation. Location: Sungai Tiang; c) Rhythmite unit of Semanggol Formation. Location: Tawar-Kuala Ketil road, Kuala Ketil; d) Chert unit of Semanggol Formation. Location: Padang Geh, Kuala Ketil. a) – c) Pencil as scale; d) Compass as scale. For locations refer to Figure 2.7.

contemporaneously with pyroclastic facies known as the Lawin Tuff (Jones, 1970). The formation lies unconformably with the neighbouring lithology in Baling: Burton (1970) have shown that the contact between Semanggol Formation and Baling Formation are faulted throughout, and in places intruded by granitic bodies. Further south from Grik, the metamorphosed rock of the Baling Formation were found to be intruded by granite and subjected to faulting, resulting in fractures, minor faults and mylonites (Ulfa et al., 2012).

Majority of Baling Formation rocks are metamorphosed, and as such not many fossils are preserved that could be used for purpose of dating. However, correlation of the fosilleferous argillaceous facies with other rock formation in the region yield a tentative Ordovician to Early Silurian age (Jones, 1970). Graptolites found in the Baling area reveal an age of Early Silurian (Jones, 1973b).

A small portion of the Baling Formation is exposed in Kupang, where it neighbours with the Semanggol Formation in Kuala Ketil. The rocks are finely foliated metamorphosed argillite, which are distinctly different from the intebedded argillaceous-arenaceous of neighbouring Semanggol Formation.

2.4.1.2 Mahang Formation

The Mahang Formation is an extensive Paleozoic aged siliclastic sedimentary rock found in southern Kedah, extending into Kulim (Courtier, 1974) and neighbouring Bedung area (Burton, 1967). The sedimentary formation is also found in central Kedah, where it is in contact with the Kubang Pasu Formation (Zaiton and Basir, 1999). Graptolites recovered from the formation give an Early Silurian age (Burton, 1967; Jones, 1973a). Lower Devonian graptolites, as well as numerous tentaculitids, were recovered as well (Jones, 1967, 1973a, 1973b).

In satellite imageries, the contact between the Bukit Perak granite and the Mahang Formation is found to be a remarkably straight linear contact. Burton (1967) identified the sharp boundary of the Mahang Formation with neighbouring granite as that of wrench fault. Exposure of the sedimentary formation could be found in the western margin of Bukit Perak, with several exposed outcrops in Gajah Putih. These outcrops reveal interbedded sandstone and shale which were subjected to minor folding and faulting. The sandstone show coarse grained yellowish to whitish colour, with fine lamination to moderately thick bedding. Some of the sandstone beds were found to show cross bedding texture. The shale and mudstone are dark greyish, and are usually interbedded along with the lighter coloured sandstone. In several localities further northwest of Sungai Tiang, the reddish slate of the Mahang Formation could be found, which shows well-developed slaty cleavage.

A small exposure of the interbedded sandstone-shale sequence of the Mahang Formation were exposed in the western part of Bina Quarry, neighbouring the granite. Here the sediment show mostly open folds, with WNW and NW trending bedding. The rocks here were found to be truncated by small sets of fractures and faults, with some developing closely spaced cleavages. Closer to the margin of the granite, the folding of the sediment intensify, forming kink folds with cleavage formation; similarly, fractures and faults occurrence in the rock increases.

In Gajah Putih, a small outcrop of the Mahang Formation rocks reveal several flank of fold hinge with different plunge direction, and this was taken to represent more than one set of deformation phases in the formation. The beddings trend predominantly north-south, mostly dipping westward. The folds plunge westward and northward, and appear almost adjacent to faults. The observed faults, based from the displaced beddings and visible fracture planes, were shown to share similar NW trend of the Bok Bak Fault.

2.4.1.3 Semanggol Formation

The Semanggol Formation is the most extensive sedimentary formation in the study area, covering the northern of Kedah and extending southward to northwest Perak. The Mid Triassic argillaceous-arenaceous rock group is generally divided to consist of three main series or members: chert, interbedded sandstone-shale (rhythmite), and conglomerate. The three group were originally introduced as members by Burton (1973), although most geologist have used the designation of units by Teoh (1992). Of the three members, the Chert Member represents the oldest unit, while the Conglomerate Member is the youngest unit (Burton, 1973). The Semanggol Formation was proposed to be in a fault contact with the Kubang Pasu Formation (Burton, 1965), with the contact was later identified to be reverse or thrust fault (Ibrahim et al., 1989). The formation develop a zone of contact metamorphism with the granite pluton of Bukit Perak (Teoh, 1992), Baling (Burton, 1970) and Kulim (Courtier, 1974), although the trace of the contact aureole is not very extensive. Where the Bok Bak Fault separates the Semanggol Formation and the granitic bodies, contact aureole were obscured by faulting.

In Sungai Tiang, the Semanggol Formation crops up northward of the granite pluton of Bukit Perak. The formation is expressed as strike ridges, which start as northeast-southwest trending parallel ridges near the Bok Bak Fault's trace. The ridges swerve to north-south set further north, near Naka (Teoh, 1992). Large exposure of the Semanggol Formation crops up in the Kuala Ketil. The rocks form sets of parallel trending ridges, similar to that observed in Sungai Tiang.

In the field, the Semanggol Formation consists mainly of interbedded sandstone, mudstone and shale, with some occurrence of chert and conglomerates. The different composition of lithology correspond to the classification by Burton (1973), although the conglomerate found is only a small occurrence. The rhythmite and chert unit is well exposed in Kuala Ketil. From field observation, the Semanggol Formation rocks were subjected to folding and cut by several sets of faulting. In areas where the rocks could be picked up as ridges in remote sensing, the general trend of the bedding appear to correspond with trend of the ridges.

2.4.2 Intrusive bodies

Several granite bodies crop out as large plutons along the trace of the fault, and these have been subjected to different naming by authors working on the different areas of granite occurrence (e.g. Jones, 1970; Burton, 1970; Teoh, 1992). Most of these granites are somewhat texturally similar, with mostly subtle difference in their mineralogical content. For this research, the granites are divided into three type based on their geographical occurrence, using the original term employed by Teoh (1992) and Jones (1970).

The granites are found as large plutons that form the highland of Bukit Perak and Bukit Enggang, and along the extent of the Baling-Gerik highway. The granites of the two hills are well exposed along the faces of quarries, and as outcropping resistant boulders amidst weathered granitic soils. Along Baling-Gerik, construction of highway provides good exposure of the granite. Elsewhere, the granite forms the lowland around the plutons, and these have been suggested to be the downthrown part of the large plutons (Teoh, 1992).

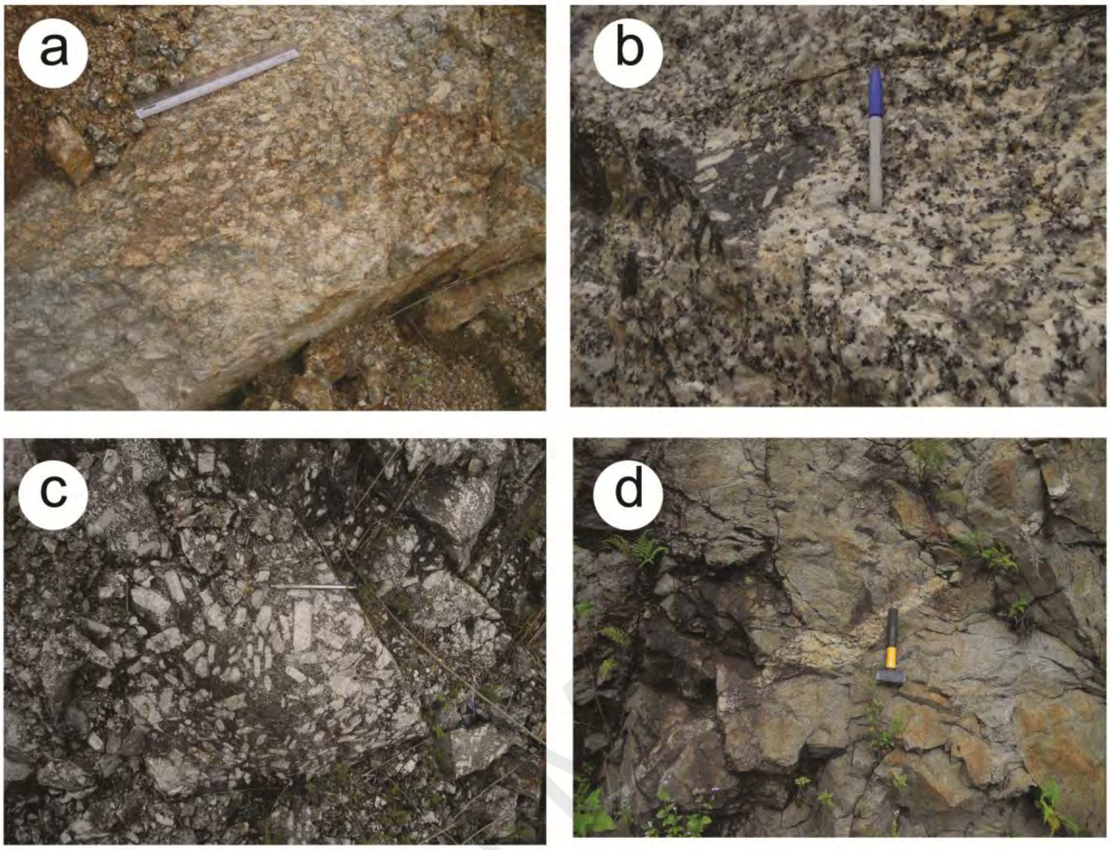

Figure 2.9: Igneous rock of the study area: a) Bukit Perak Granite. Location: Pati Quarry, Sungai Tiang; b) Bukit Enggang Granite. Location: TAHB Quarry, Jeniang; c) Bintang Hill Granite. Location: Baling-Grik highway; d) Pegmatitic dike in Bintang Hill Granite. Location: Baling-Grik highway. a) Ruler as scale; b) – c) Pencil as scale; d) Hammer as scale. For locations refer to Figure 2.7.

2.4.2.1 Bukit Perak Granite

Teoh (1992) used the term Bukit Perak Granite to describe coarse porphyrytic leucocratic granite, with mottling of black biotite and large white feldspar megacryst. These granites occur in the Bukit Perak massif, and could be found along Bina Quarry, Pati Quarry, and Oscar Quarry. The granites are mostly leucocratic with porphyrytic texture, the white feldspar forming the clast. Quartz, alkali feldspar, plagioclase and biotite make up the constituent of the granite. Accessory minerals include chlorite. Feldspar and biotite show alteration texture, with the latter altered to chlorite. From mineral composition, majority of the granite could be allocated as alkali granite, with some granodiorite (Teoh, 1992).

Magmatic flow in granite, shown by arrangement of feldspar clast, is observed in some localities. The relation of magmatic flow with faulting is rather ambiguous: although the trend of the feldspar foliation show parallelism with the trend of certain faults, in other place, the foliation doesn't follow the trend of nearby faults. Given these ambiguous indicator, it is most likely that these clasts were affected by magmatic flow as opposed to shearing along the fault zone. Sheared granite produce cataclastic and mylonitic granite. The mylonitized granite is well observed along the western part of Bina Quarry in Sungai Tiang. Elsewhere, shearing in the granite produce brecciated and fractured granite.

On the southeast of Bukit Perak near the Lubok Merbau area, large bodies of quartz vein could be found outcropping amongst the weathered granitic soil. The quartz body form whitish boulders and cobbles in the field, with exposure of several hundred meters. They are rather heavily fractured and on several occurrence shows brecciated texture. Despite heavy fracturing, the quartz are solid and consolidated. Teoh (1992) and Abdullah (1993) have reported instance of large quartz vein formed along NE trending fault, which borders with the NW fault of main Bok Bak Fault. Both authors believed the quartz were formed post-faulting.

2.4.2.2 Bukit Enggang Granite

The Bukit Enggang Granite forms the Bukit Enggang massif, with the granites well exposed along the quarries of TAHB Granite Quarry and BKLS Quarry. The granites were reported to be texturally similar to the Bukit Perak Granite (Teoh, 1992), being leucocratic and of porpyhrytic texture. The granite could be taken as an extension of Damar Granite in Baling area by Burton (1970).

As with Bukit Perak Granite, majority of the granite have porphyrytic texture, feldspar forming the clast. The granite is composed of quartz, alkali feldspar, plagioclase and biotite, with accessory minerals such as chlorite and epidote. Most of the biotite in the granite was altered to chlorite: in sheared granite, this result in a greenish colour. Compared to the Bukit Perak granite, myrmekitic intergrowth texture between feldspar and quartz could be observed under microscope. Tourmaline crystals are found as intergrowth in some of the veins, and this is well observed in TAHB Quarry where the tourmalines could be seen forming veins with epidote as acicular crystals. Small traces of xenolith were also observed in the granite. The granites are mostly classified as adamellite and alkali granite (Teoh, 1992). Pegmatitic granite is well observed in BKLS Quarry, in the form of irregular bodies and large veins: the granite here is less porphyrytic and coarser grained compared to other granite.

2.4.2.3 Bintang Hills Granite

Jones (1970) have designated the porphyrytic and sheared granite west of Gerik as the Bintang Hills Granite. Much like the granite of Bukit Perak and Bukit Enggang, the granite exhibit porphyrytic texture, with feldspar forming the clasts. The author however doesn’t allocate a detailed subdivision of the granite: Burton (1970), who subsequently mapped the granite in the area, has subdivided the granite bodies of Kupang, Inas and Damar Granite. It was however maintained that the naming of Inas Granite is applied to one of the varieties of granite forming the Bintang Range (Burton, 1970): thus, the term Bintang Hill Granite used by Jones (1970) could be said to be a general term to cover the granite exposed in the area. For this work, the term Bintang Hills Granite is used as a general term for all granite which outcrops along the Baling-Gerik highway.

The granites are leucocratic, coarse grained with porphyritic texture. Feldspar makes up the clast, with other minerals consisting of quartz, alkali feldspar, plagioclase, mica and other accessory minerals forming the groundmass. Flow banding of the porphyrytic granite is well observed in most exposure. Biotite form most of the mica in the granite, and these show exceptional mica fish microstructure when they are deformed. The biotite from the granite seems much abundant and intact compared to the other two granitic bodies, and secondary biotite which forms the foliation of mylonitic granite are quite common where the granite is sheared. The granites show a much more distinct shearing feature, producing both brittle cataclasite and mylonite.

There is also a small occurrence of microgranite alongside the porphyritic granite. Through several extent of the area, quartz veins with tourmaline content intrude into the granite. While most of these occur as isolated veins, in several localities the veins form a zone with sets of veinlets. Pegmatitic dikes could also be found intruding into the porphyrytic granite. Compared with pegmatitic granite of Bukit Enggang, these seem to be more abundant in mica content. The dikes seem to postdate shearing, as some has exhibited evidence of being folded.

2.4.2.4 Other igneous bodies

Burton (1970) designated the granite bodies in Baling to Inas Granite, Damar Granite and Kupang Granite, allocating them to the localities and different intrusion period. The southeastern granite extension off Bukit Enggang was given the term Rimba Telui Granite (Teoh, 1992), where the contact with adjacent Bukit Enggang Granite is defined by NE-SW trending fault. The majority of the Rimba Telui Granite is reported to be adamellite (Teoh, 1992). From their mapped extent, the Rimba Telui Granite appears to be the northwestern extension of Burton's Damar Granite. Similarly, the Bukit Enggang Granite could be correlated with Inas Granite in Baling. The Bukit Perak Granite doesn't appear to have immediate extension with the granite classification by Burton, although it was noted to be texturally similar with Inas Granite, Bintang Range Granite and Main Range Granite (Teoh, 1992).

Several of the mapped intrusive bodies were separated by faults: NW set faults separate Kupang-Inas Granite, while NE set faults separate Bukit Perak-Bukit Enggang and Bukit Enggang-Rimba Telui Granite. The Damar Granite doesn't show a clear boundary with the faults in geologic map: report of intrusion of granitic bodies similar with Damar Granite along the main NW trend fault have gave rise to the idea that not only the Damar Granite is the youngest among the granite intrusion, but is also of the same time with movement along the Bok Bak Fault (Burton, 1970). There is however no strong field evidence for the granite being syn-kinematic in respect with the Bok Bak Fault.

2.4.3 Summary for geology of Bok Bak Fault Zone

The geology along the Bok Bak Fault Zone is characterized by sedimentary rock unit and granitic igneous bodies. Field checks have confirmed the occurrence of these rock units which have been discussed in greater detail by previous workers.

The Baling Formation rock unit is exposed in Kupang, where it neighbours with the Semanggol Formation in Kuala Ketil. The rocks are finely foliated metamorphosed argillite, which is distinct from the rest of the sedimentary rock unit. Rock from Mahang Formation neighbor granitic bodies in Sungai Tiang, and show evidence of multiple deformation from the occurrence of several different plunging folds. The Semanggol Formation is exposed in Sungai Tiang and Kuala Ketil area, with the occurrence of folding beds and faulting. Both Mahang Formation and Semanggol Formation rock appear to form sets of parallel trending ridges, and these will be discussed in Chapter 3.

Granites form the large plution of Bukit Perak and Bukit Enggang, and a portion of the Baling-Gerik highway. As a result of deformation, various products of sheared granites were produced in the granite plutons. The resulted fault rocks are found to be generally distinct in texture from that of undeformed granites, and could be differentiated both in the field and microscopy. The property of these faulted granites and the deformation mechanism which result in their formation will be discussed in Chapter 4 and 5.

CHAPTER 3: REMOTE SENSING STUDY

3.1 Introduction

Studies on aerial photographs and satellite imageries have proved important in the study of the fault systems of the Peninsula. With time, more advanced and higher resolution images in satellite imageries helped to further mapped out fault zones in greater detail. The work by Raj (1982) is a comprehensive lineament studies on the Bok Bak Fault, where the fault trace was extended into Central Perak and Kelantan based on lineaments plot and distribution of lithology. Subsequent use of lineament study, supplemented with field check, was used in southward extension into Perak (Abdul Majid, 1987) and northwestward extension into Perlis (Syed, 1995).

In this study, a combination of DEM-SRTM data, satellite imageries and aerial photograph along the main trend of the fault zone were used in studying pattern of the lineaments. The trend of these lineaments was compiled, analyzed, and interpreted.

3.2 Lineament extraction

Distinctions are made between negative and positive lineament: the former refers to linear structures with low relief, and the latter refers to high relief linear structures. The two types of linear structures are distinguished for the purpose of correlating with structural data.

From the various method of lineament extraction discussed in Chapter 1, regional lineament study was conducted mostly by using lineament extracted from Digital Elevation Model-Shuttle Radar Topographic Mission (DEM SRTM) imagery. This method has several advantages over relying on simply one set of aerial photographs and/or satellite images, having more flexibility for lineament plotting and analysis as well as having significant accuracy in lineament detection. The most significant advantage is the creation of hill shading: DEM was extracted from SRTM, where it is applied with different azimuth direction and sun angle. This technique is useful in enhancing geological and geomorphological feature, which might not be visible had only aerial photograph of LANDSAT images are used. The hill shading image was created from an input angle of 45°, 90°, and 135°. These angles were chosen to prevent bias of lineament picking from only using one input angle, and were chosen due to their relation with trend of major faults reported by other works (NW-SE, N-S, and NE-SW respectively)

Lineament data (azimuth and length) are plotted graphically as radar graph in spreadsheet program (MS Excel). The lineament data are separated into an interval of 10°, with the cumulative length of each interval calculated. This produce a more accurate representation of the lineament distribution, rather than plotting the data solely based on the azimuth of each lineament without consideration of the length of each lineament's group: plotting of lineaments sets without taking into consideration the length could potentially mean that minor short length lineaments which occur in scattered group might have a bigger representation graphically when they are plotted alongside major lineament set.

3.3 Geological domains

3.3.1 Lithological domains

As the Bok Bak Fault consist of several rock unit, for the purpose of lineament analysis, the area is divided into several domains, based on lithology and geographical location (Figure 3.1). The domains are divided based on rock unit from field mapping, as well as previous mapping of Burton (1972), Raj (1982), and Teoh (1992). The division of domains based on rock unit is to study if there is significant change of lineament density and trend in different geology. For the purpose of this chapter, additional rock units that are cut by Bok Bak Fault yet not covered by field visit in this study will also be included:

1) Western Paleozoic Sediment Domain (WPAL)

2) Eastern Paleozoic Sediment domain (EPAL)

3) Mesozoic Sediment Domain (MES)

4) Granite Domain (GR)

5) Tertiary Sediment Domain (TER)

6) Quaternary Sediment Domain (QTY)

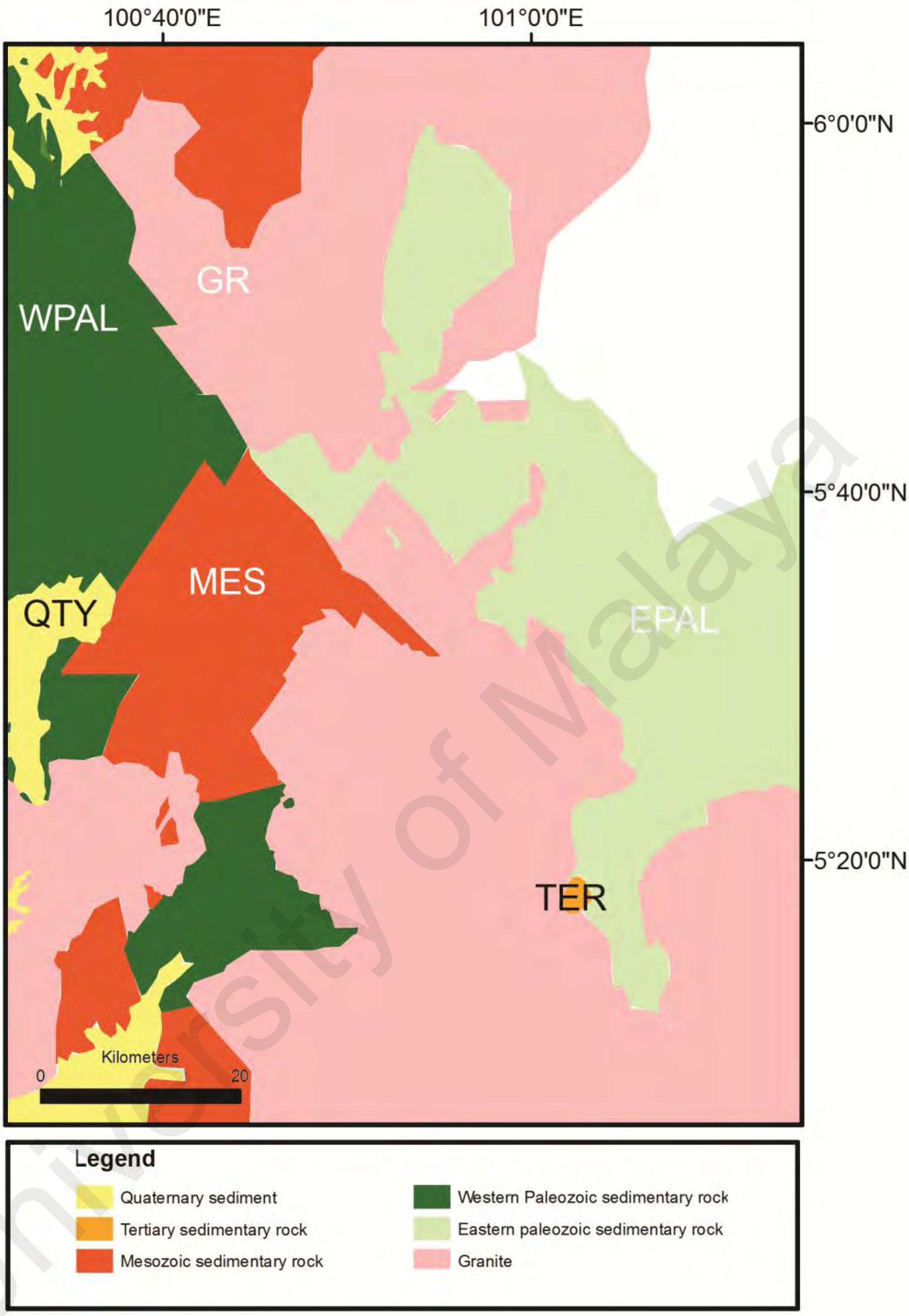

Figure 3.1: Lithological domain of the study area. Geology from field mapping and Burton (1972), Raj (1982), and Teoh (1992).Refer to Figure 2.6 for geological map of study area.

3.3.2 Geomorphology

The study area is characterized by hills and valleys (Figure 1.3). The Western Paleozoic Sediment Domain (WPAL) forms N-S trending hills, covering an area of 2047.45 km^2. Majority of the lineaments are positive lineaments, which correspond to the trend of the hills. The negative lineaments are mostly concentrated in sections adjacent to granite bodies. Most of the observations here have not been noted in other work relating to the Bok Bak Fault:

The Eastern Paleozoic Sediment Domain (EPAL) shows similar feature with WPAL, having N-S trending hills. The domain covers an area of 1446.22 km^2. Compared to WPAL, some of the hills show E-W trend, and this is corresponded with the positive lineaments. The domain also shows high concentration of negative lineament in part which borders granite.

The Mesozoic Sediment Domain (MES) is made up primarily by the Semanggol Formation sediments, which forms long narrow hills trending N-S and E-W. The hills are much more prominent than the Paleozoic Sediment Domain. The domain covers an area of 1363.69 km^2. A number of negative lineament cuts the domain, and the positive lineament is very distinct, the latter showing clear change of trend across the subdomains.

The Granite Domain (GR) consist of granitic body which covers a large area, in irregular bodies trending roughly N-S. The domain covers an area of 6794.54 km^2. The domain forms the highest points in the area, visible as large hills and mountains.

The Tertiary Sediment Domain (TER) refers to a very small spot of sediment in northern Perak. The sediment is of semi-consolidated, interstratified sand, grit, and pebble beds (Jones, 1970). It is the smallest of the domains, at only 7.78 km^2. The domain is only mentioned here as a subdivision of geologic bodies in the area, since the small distribution of the sediment does not provide much room for detailed lineament analysis.

The Quaternary Sediment Domain (QTY) is formed at the coastline in the west, as well as a few notable large occurrences north of the area. It consists of unconsolidated sediments, covering an area of 1449.45 km^2. Several small lineaments appear to cut the domain, but these appear to be further extension of lineaments in neighbouring domains and are thus not counted for lineament analysis. The domain has distinctively low topography, consisting of flat plains which contrast with the elevated area of other domains.

3.3.3 Lineament-fracture correlation domains

For detailed study on correlation between lineament and geological structures, the area have been subdivided into grids (Figure 3.7), based on the categorization by Moore et al. (2002) on lineaments and fracture correlation. The methods aim to find correlation between lineaments extracted from remote sensing with fractures from field checks. Three analysis techniques are mentioned:

1) Unfiltered lineament analysis technique, involving comparison of all lineament data with fracture data of entire area;

2) Filtered, domain-based correlated lineaments analysis, determined by defining fracture family for each grid;

3) Filtered, discrete-analysis-based fracture correlated lineaments, where structural data is defined for each grid; lineaments in a particular grid are compared with strike of planar structural feature in the same grid.

In subsequent writing of this chapter, the term fracture is used to encompass both joints and fault when correlating with lineaments. Kinematic study of faults in the field is covered in Chapter 5.

3.4 Lineament analysis

3.4.1 Lineament distribution

3.4.1.1 Aerial photographs

Aerial photographs are studied under stereoscope, which illustrated a three-dimensional view of the area. Black and white vertical stereo-paired aerial photographs of the scale 1:25000 are used for this study. Lineaments plotted were transferred to a map scale of 1:50000 (Figure 3.2).

The result of lineament interpretation show major trend at 60° (ENE-WSW), 90° (E-W) and 140° (NW-SE).

3.4.1.2 Satellite image

The study use LANDSAT image sets from the year 1990 with 28m resolution, and a year 2000 image with 14.5m resolution. Both satellite images are in UTM Zone 47 projection. The plotting of the lineament is done entirely manually over the images. For

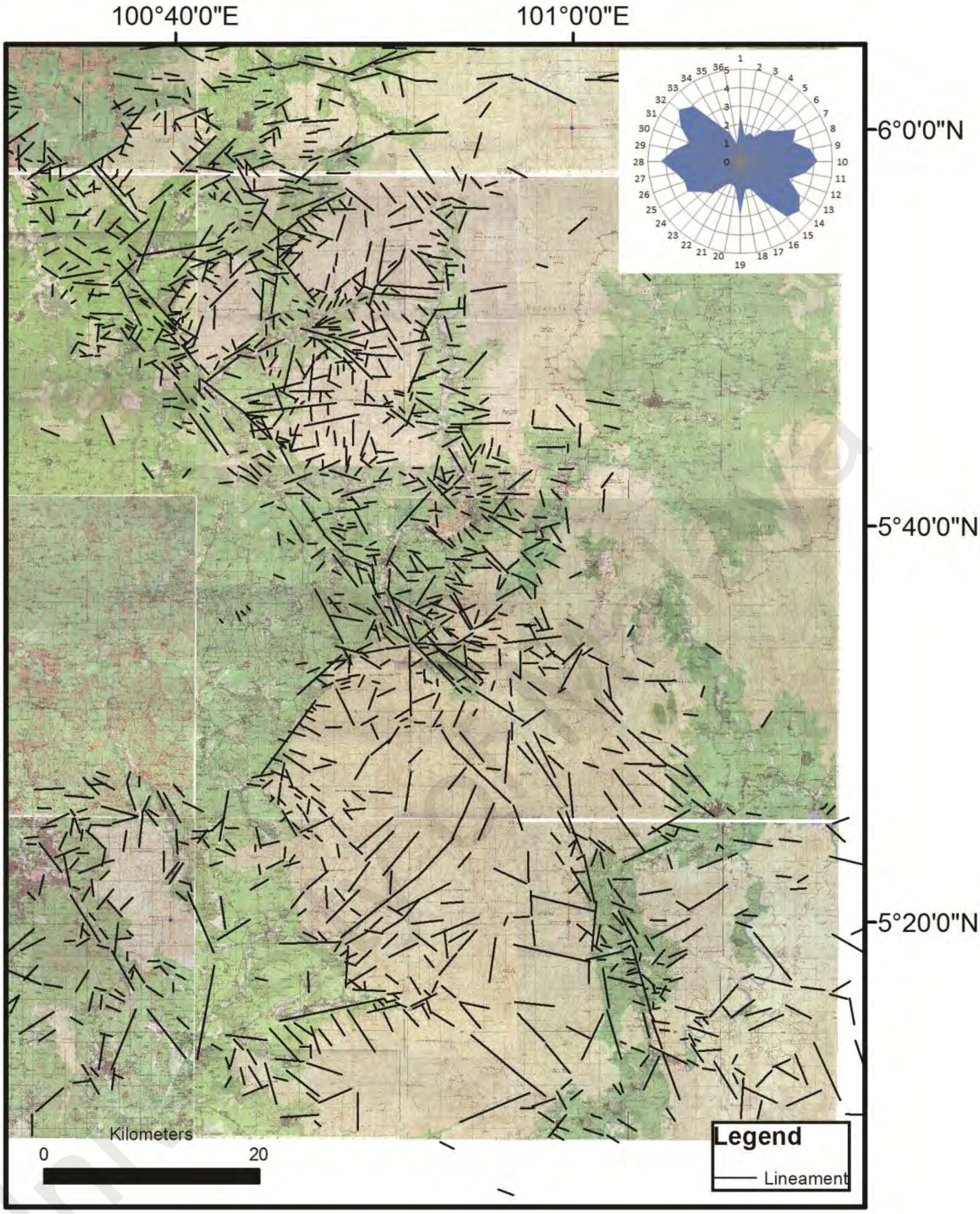

Figure 3.2: Aerial photograph lineament interpretation, plotted on series of 1:50000 scaled topographic map. Lineaments show maxima at 60° (ENE-WSW), 90° (E-W) and 130° (NW-SE).

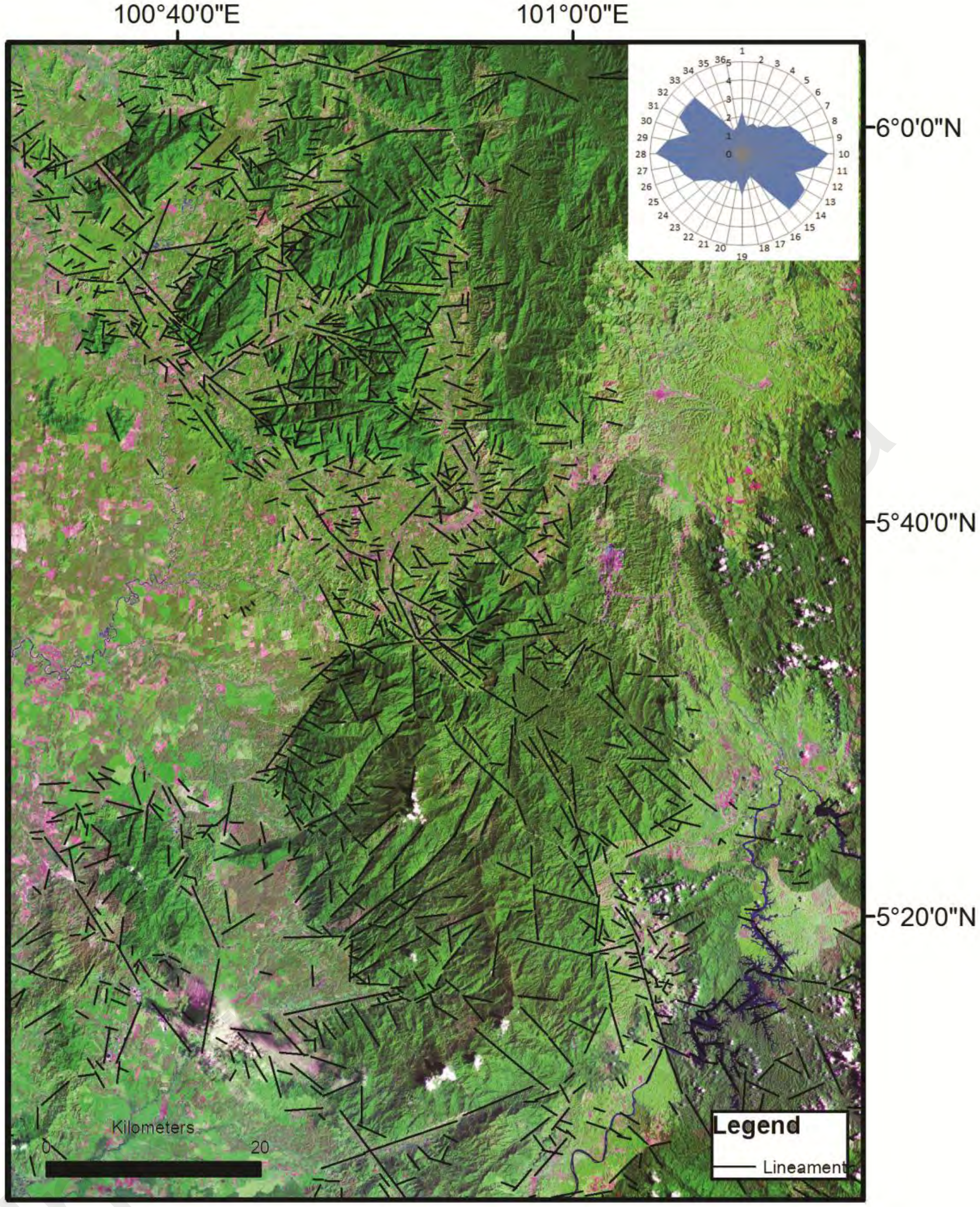

Figure 3.3: LANDSAT lineament interpretation, plotted on LANDSAT image, *year 1990, with* 28m resolution. Lineaments show maxima at 90° (E-W) and 140° (NW-SE).

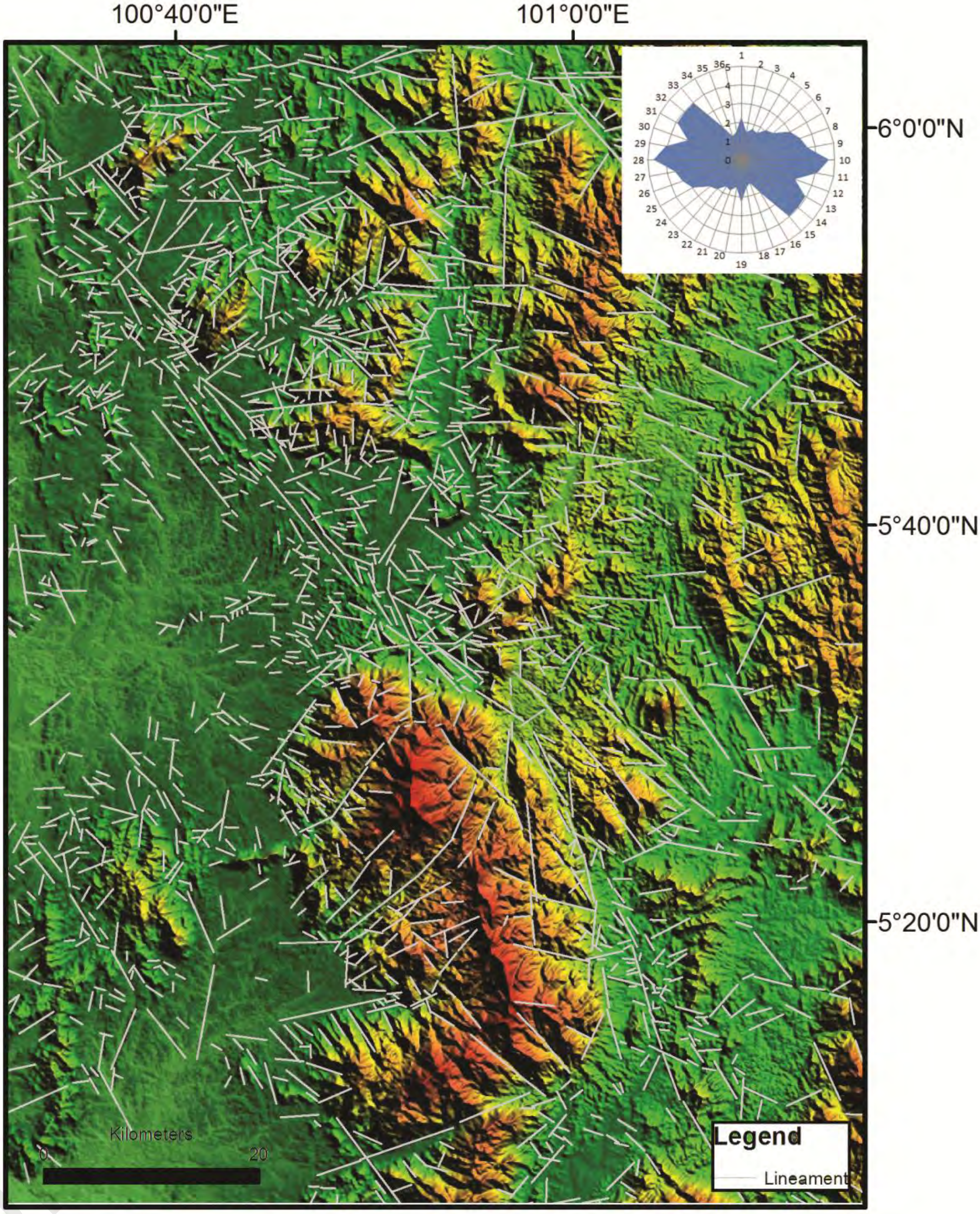

Figure 3.4: DEM-SRTM lineament interpretation, plotted on hillshade map generated from SRTM digital elevation model (sunlight attitude: 045°). Lineaments show maxima at 90° (E-W) and 140° (NW-SE).

the study, the year 1990 image is primarily used in the plot of the lineaments due to its clearer image. Lineaments are plotted manually through ArcMap software (Figure 3.3).

The result of lineament interpretation show major trend at 90° (E-W) and 140° (NW-SE).

3.4.1.3 DEM-SRTM

DEM-SRTM is used primarily for lineament analysis. SRTM digital elevation model is processed by ArcGIS software to produce hillshade maps. Shaded relief images were produced from lighting azimuth of 0°, 45°, and 90°, and these were chosen to prevent bias of lineament picking by only using one lighting azimuth. Lineaments are plotted manually through ArcMap software (Figure 3.4).

Lineament interpretation of the data show major trend at 90° (E-W) and 140° (NW-SE).

3.4.2 Unfiltered lineament analysis

An initial unfiltered lineament analysis was carried out to compare trend of lineament and structural trend in whole area. An unfiltered lineament analysis refers to a quick correlation analysis between all lineament of study area with their respective geological elements. Negative and positive lineaments plotted were distinguished, where they are compared with their geological elements (fractures and bedding trend respectively) (Figure 3.5). The data used are from the DEM-SRTM extraction (Figure 3.6), as the imageries provide the most variables for extraction and interpretation of the lineaments.

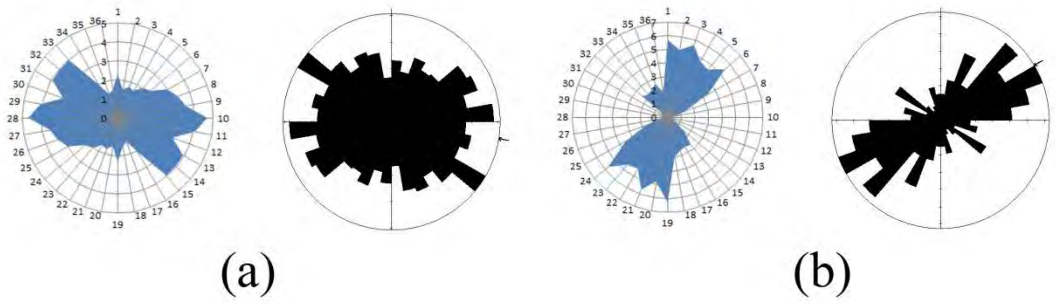

Figure 3.5: Rose diagram for (a) negative lineament and fracture orientation; and (b) positive lineament and bedding orientation

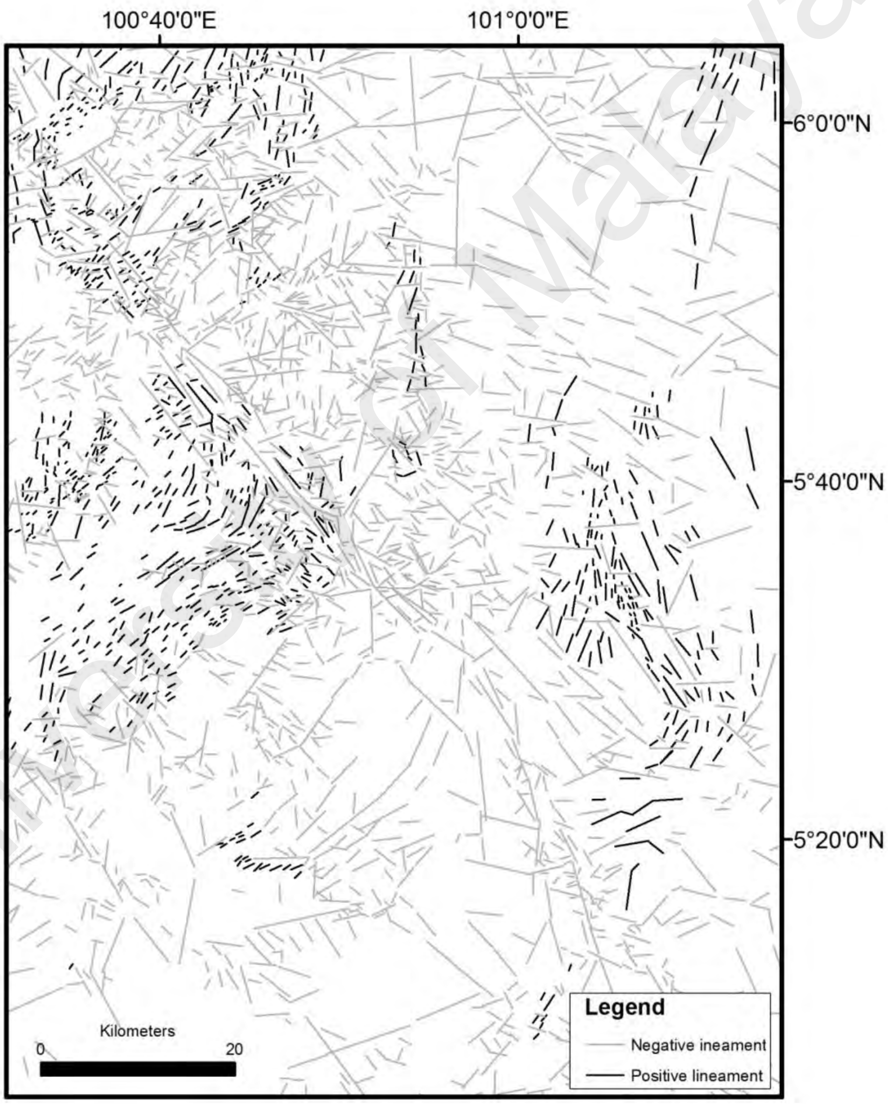

Figure 3.6: Negative and positive lineament extracted from DEM-SRTM

The unfiltered lineament analysis for negative lineament and fracture shows the lineament with maxima trend at 100° and 140° (E-W and NW-SE), and fracture with maxima trend at 090° and 130° (E-W and NW-SE). For unfiltered positive lineament analysis, the lineaments and bedding show a significant discordance between one another, where the positive lineament show maximum trend towards 010° (N-S), while bedding maximum trend towards 070° (ENE-WSW).

3.4.3 Lineament pattern of grid cells

For the purpose of filtered, discrete-analysis-based fracture analysis, the total study area has been divided into 12 grid-cells, each with dimension of 30 km x 30 km, or an area of 900 km^2, for the domain-based fracture-correlated lineament analysis (Figure 3.7). The size of the grid was chosen arbitrarily based on the overall size of available data from remote sensing and rock unit: each grid would effectively cover certain rock units, and a quick analysis of the lineament pattern in each lithological domain is possible.

Although the lineament varies in each grid, two significant trends are observed among the grids: maxima at 90° (E-W) and 130° to 140° (NW-SE). This is comparable with the trend shown by the unfiltered lineament analysis, as well as that observed in some of the individual lineament distribution analysis (Figure 3.3 and Figure 3.4).

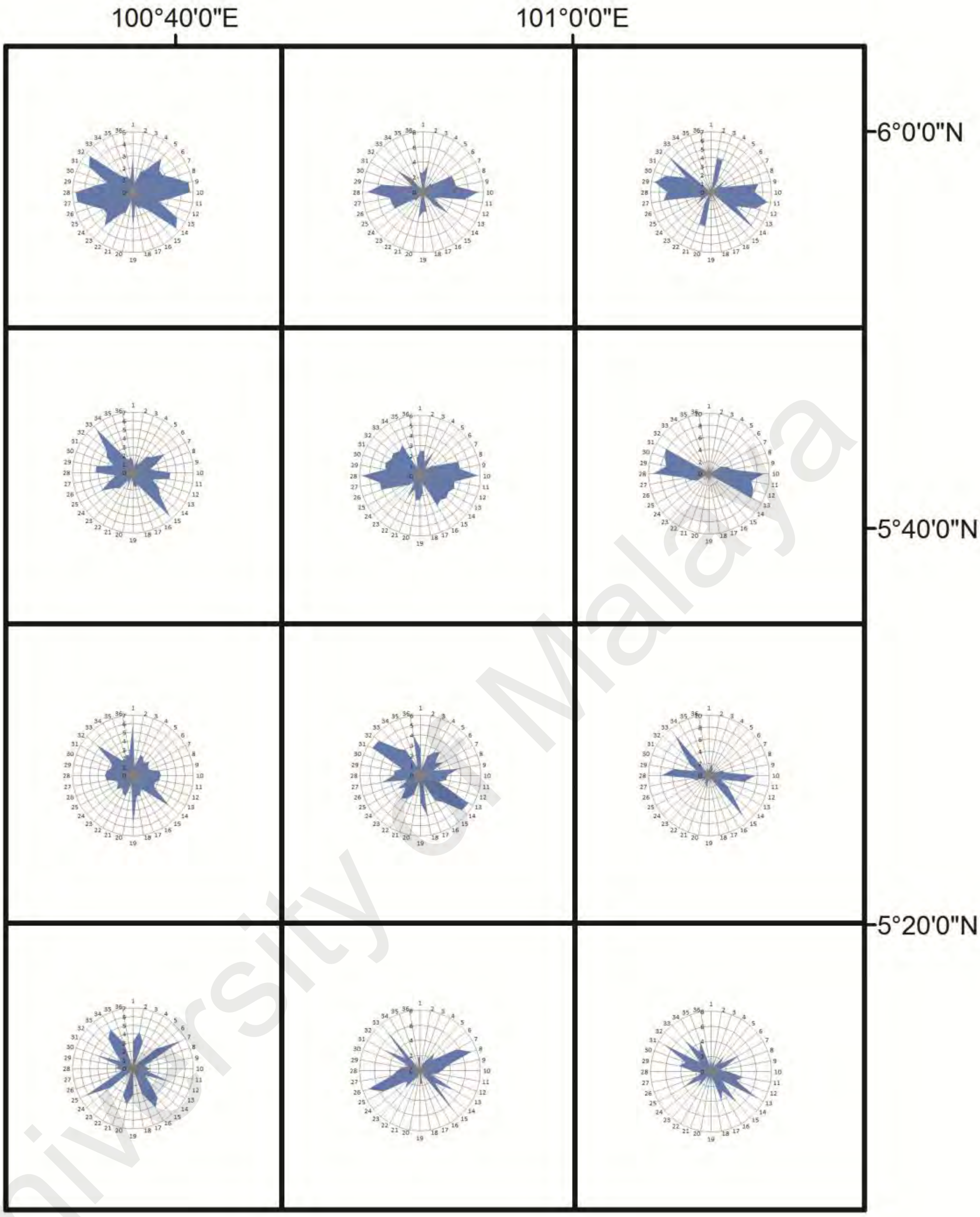

Figure 3.7: Map showing spatial distribution of negative lineament in grid cells (30km x 30 km in size)

3.4.4 Lineament pattern of lithological domain

A summary of the trend of negative and positive lineament for the lithological domains is shown in Table 3.1 and Figure 3.8. Both WPAL and GR domains show trend maxima at 130° (NW-SE) for the negative lineament. EPAL domain show a maximum trend of negative lineament at 090° (E-W). MES domain show maximum trend of negative lineament at 080° (E-W). For the positive lineament, the maximum trend is 050° (NE-SW) for WPAL and MES, and 0° (N-S) for EPAL.Both TER and QTY domains have negligible number of lineament traversing them, and are not represented here.

3.4.5 Lineament and field data correlation

A more detailed study for the lineament is correlating between lineament distribution, and geological structure lithological domain and field data. From the grid cells of the whole area, only a portion was traversed through field mapping. Four main lithology type are mapped in the whole area: the Baling Formation (East Paleozoic Sediment Domain), the Mahang Formation (West Paleozoic Sediment Domain), the Semanggol Formation (Mesozoic Sediment Domain), and the Bukit Perak Granite, Bukit Enggang Granite, and Bintang Hills Granite (Granite Domain). The lineament and fracture trend data recorded from these lithologies are shown in Table 3.2, and the rose

Table 3.1: Major lineaments in the lithological domain

Lithological domain	Major negative lineament trends
West Paleozoic Sediment	NW-SE
East Paleozoic Sediment	E-W
Mesozoic Sediment	E-W
Granite	NW-SE

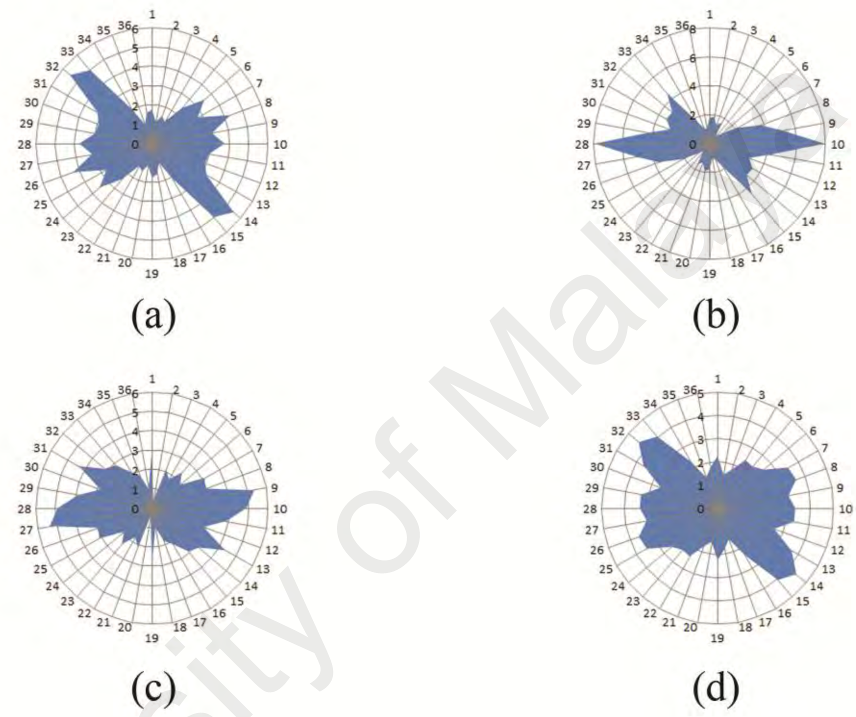

Figure 3.8: Rose diagram showing negative lineament orientation in lithological domains: (a) WPAL; (b) EPAL; (c) MES; (d) GR

Table 3.2: Comparison of major lineaments and structure trends in the mapped lithological unit

Mapped rock unit	Major negative lineament trend	Major fracture trend	Major positive lineament trend	Major bedding trend
Mahang Formation	NW-SE	NNW-SSE	N-S	NE-SW
Baling Formation	E-W		NE-SW	NE-SW
Semanggol Formation	WNW-ESE	NW-SE	NE-SW	NE-SW
Bukit Perak-Bukit Enggang Granite	NW-SE	NW-SE		
Bintang Hills Granite	NW-SE	ENE-WSW		

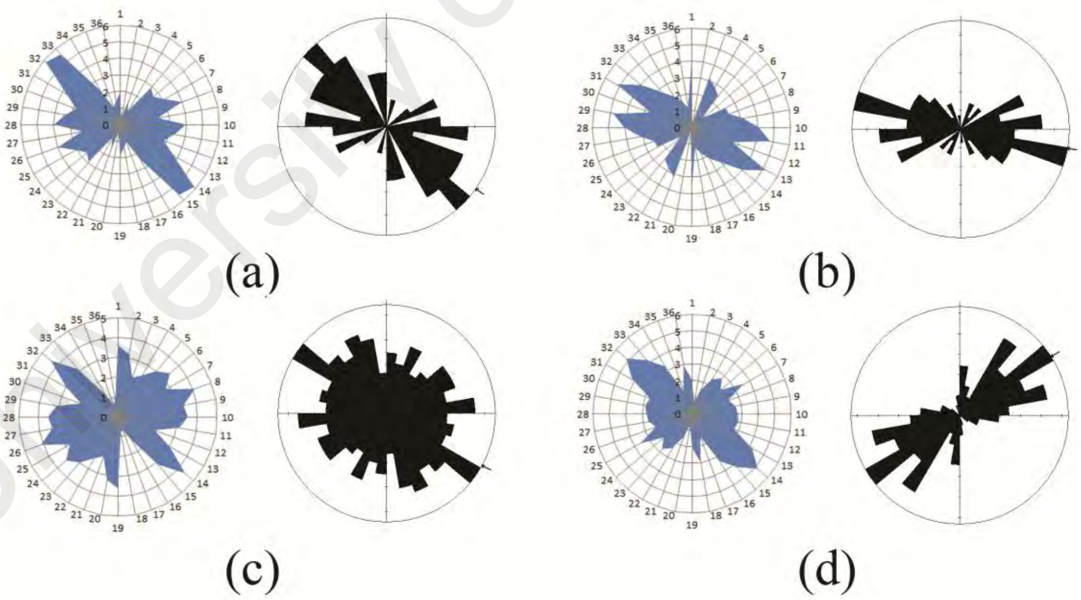

Figure 3.9: Rose diagram showing negative lineament orientation and fracture orientation in mapped rock unit. (a) Mahang Formation; (b) Semanggol Formation; (c) Bukit Perak and Bukit Enggang Granite; (d) Bintang Hills Granite

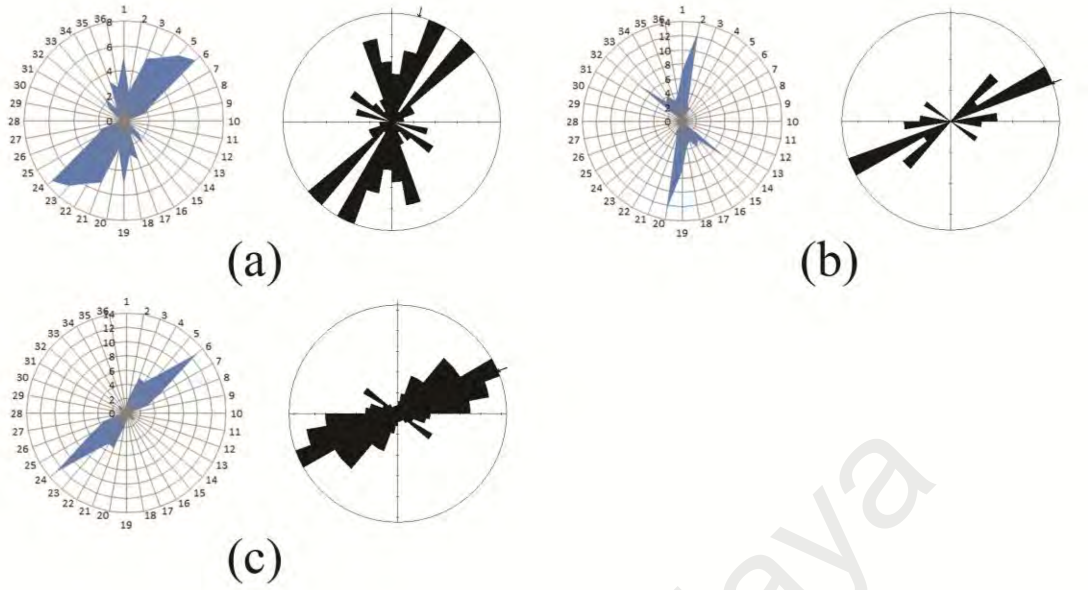

Figure 3.10: Rose diagram showing positive lineament orientation and bedding orientation in mapped rock unit. (a) Baling Formation; (b) Mahang Formation; (c) Semanggol Formation

diagram in Figure 3.9 and Figure 3.10 show the relationship the effects of lithology to them.

Sedimentary rock of Mahang Formation is cut by 130° (NW-SE) negative lineament, and show fracture at 150° (NNW-SSE). Semanggol Formation sediment is cut by 120° (WNW-ESE) negative lineament, and fractures at 130° (NW-SE). Both the Bukit Perak and Bukit Enggang Granite, and Bintang Hills Granite is cut by negative lineament trending at 130° (NW-SE); the Bukit Perak and Bukit Enggang Granite fractures trend of 130° (NW-SE), while the Bintang Bills Granite fractures trend 060° (ENE-WSW).

The Baling Formation forms 010° (N-S) positive lineament, and in the field has 050° trending (NE-SW) bedding and foliation. Both Mahang Formation and Semanggol Formation show similar trend, where they forms 050° (NE-SW) positive lineament, and in the field has bedding trend of 050° (NE-SW).

With the exception of the Bintang Hills Granite, comparison of lithology and the negative lineaments show comparable trend. Similar observation is observed for comparison between lithology and positive lineament (with the exception of Baling Formation). This would indicate that the lineaments produced are the result of fractures and bedding in the lithology.

3.4.6 Discussion

From analysis of the lineaments, a striking difference could be seen in the trend of lineaments in granitic body and sedimentary formation: negative lineaments' density is very high in granite bodies. The density of the lineaments is considerably higher near the vicinity of the main trend of the fault zone, regardless of the rock unit. The negative lineaments are therefore an expression of fractures and faults present in the rock unit.

In contrast to this, positive lineaments are prevalent in sedimentary rocks, forming continuous sets of strike ridges over considerable distance. They are a direct expression of the sedimentary rock bedding. The strike ridges are strongly deflected near trace of the main Bok Bak fault, although some also show dragging in vicinity to granite plutons. The strike ridges north of the Bukit Perak pluton, for example, show sign of drags as they approach the granite body, without the presence of major fault zone (Figure 3.11).These strike ridges in the area were bent and dissected by traces of minor conjugate faults, suggesting that faulting is also responsible in addition to granite intrusion in forming the trend of strike ridges observed (Figure 3.6).

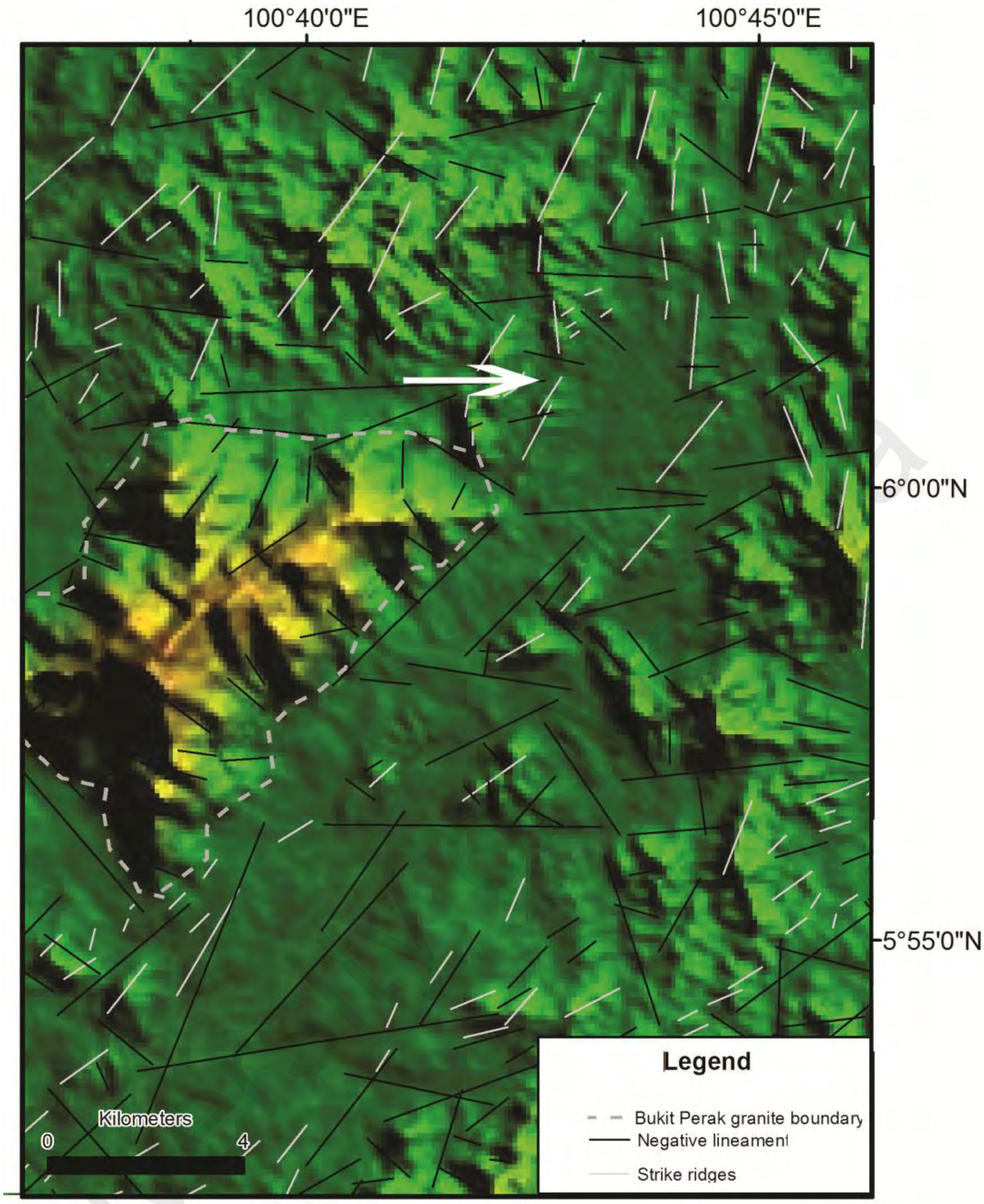

Figure 3.11: Drag of strike ridges near the Bukit Perak granite body. Arrow indicate the effect of drag observed near the granite body.

3.5 Structural interpretation of lineament

A problem with using lineaments directly from remote sensing is in differentiating the origin of these lineaments – whether they are the result of tectonic activity, or are of non-tectonic origin. A few studies attempted to construct a kinematic model for the Bok Bak fault, by using a combination of remote sensing and field data:

Raj (1982) interpreted the NW-NNW and NE-ENE trending lineaments in Kedah-Perak to represent strike of first and second order strike slip faults that are associated with major left-lateral fault zone. Interpretation of these lineaments have resulted in the recognition of extensive left-lateral displacement of rock unit in Perak.

Ibrahim et al. (1989) by studying the lithofacies boundary in Semanggol Formation rocks of Kedah and Perak, pointed out that trend of strike ridges in the rock unit are the result of clockwise rotation from granite intrusion and left-lateral movement of Bok Bak Fault.

3.5.1 Strike ridges interpretation

The strike ridges, represented as positive lineaments (Figure 3.11) are visible structures which are important in interpreting the movement along the Bok Bak Fault. Indeed, previous studies have used these as the basis for establishing the kinematic of fault zone (e.g. Ibrahim et al., 1989; Mustaffa, 1994; Syed, 1995). From lineament plotting, the strike ridges show Z shaped trend close to the main trend of the Bok Bak Fault (Figure 3.12). This is indicative of drag folds formed by sinistral strike slip faulting.

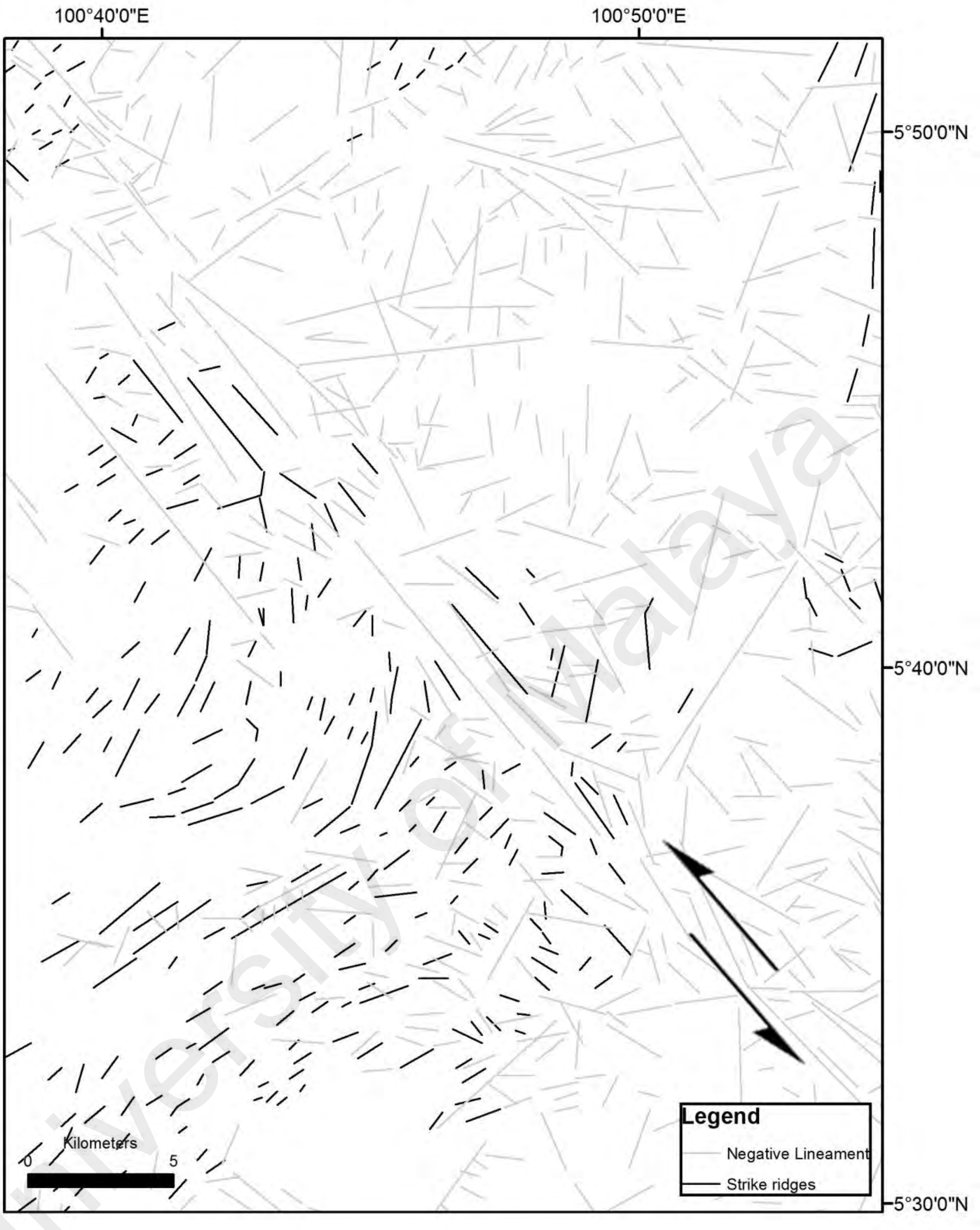

Figure 3.12: Z-shape of strike ridges adjacent to lineament along main trace of Bok Bak Fault. Sense of shear interpreted as left lateral. Lineaments extracted from DEM-SRTM.

The sinistral movement along the Bok Bak Fault was believed to be responsible for the formation of folding and reverse faulting adjacent to the fault zone, and the these structures were said to characterize transpressive tectonic environment along the fault zone (Zaiton, 2002). While granite intrusion might have played some role in causing the drag observed in some of the strike ridges (Ibrahim et al., 1989), the overall movement along the main fault zone is the most significant in producing the drag observed in the strike ridges.

3.5.2 Cross-cutting relationship of lineaments

The NW-SE negative lineament is the earliest to develop among the negative lineaments, where it is in turn cut by later lineament sets. These NW-SE lineaments form the main left lateral strike slip Bok Bak Fault, in which its movement cause the drags observed in the strike ridges. NE-SW negative lineaments cut the earlier lineament sets, and right lateral strike slip along these result in an en echelon trend for the main fault zone (Figure 3.6). The NE-SW sets do not appear to cause significant drag along strike ridges. E-W lineaments cuts the other lineaments set, but does not seem to produce any observable sense of movement.

3.5.3 Riedel Shear interpretation of lineaments

One method in interpreting the lineament and how they relate with each other is by using the Riedel Shear model. This is done by interpreting the lineament in a strike-slip tectonic framework.

By comparing the lineament trend with an idealized sinistral simple shear model (Figure 3.13, Table 3.3), the major NW-SE lineament set is interpreted as the main shear (Y shear), representing the major strand of the Bok Bak Fault Zone. WNW-ESE and NNW-SSE represents synthetic R-shear and P-shear respectively, and NE-SW lineaments represents associated antithetic R'-shear. E-W lineaments would represent fracture sets, which are widespread among all rock units, as well as normal fault sets. These structures in the field will be discussed in detail in Chapter 4 and Chapter 5.

The strike ridges formed adjacent to the main fault zone appear compatible in a Riedel Shear model, where they could be described as right-handed in relation to the main fault zone (Figure 3.12). This, along with the distribution of reverse faults and thrust faults, appear to be one possible basis for the interpretation of the Bok Bak Fault as undergoing transpressive deformation by Zaiton (2002).

3.6 Summary of remote sensing studies

Remote sensing studies of area transected by the Bok Bak Fault Zone have shown the presence of lineaments in the different rock units, and lineament analysis was carried out based on the subdivision of lithological domain to study the relationship between lineament and rock units. Six lithological domain was identified, each corresponding with rock units mapped in the field. Comparison between lineaments, and lithology and structures generally show comparable trend, thus indicating that lineaments were controlled by fractures and bedding in the lithology. Granites generally show higher density of negative lineaments, whereas positive lineaments are observed in most sedimentary rock units. By studying the trend of these lineaments and how they relate to the rock unit, it is possible to characterize the trend of structures associated with the Bok Bak Fault, as well as interpret the movement along the fault zone from the

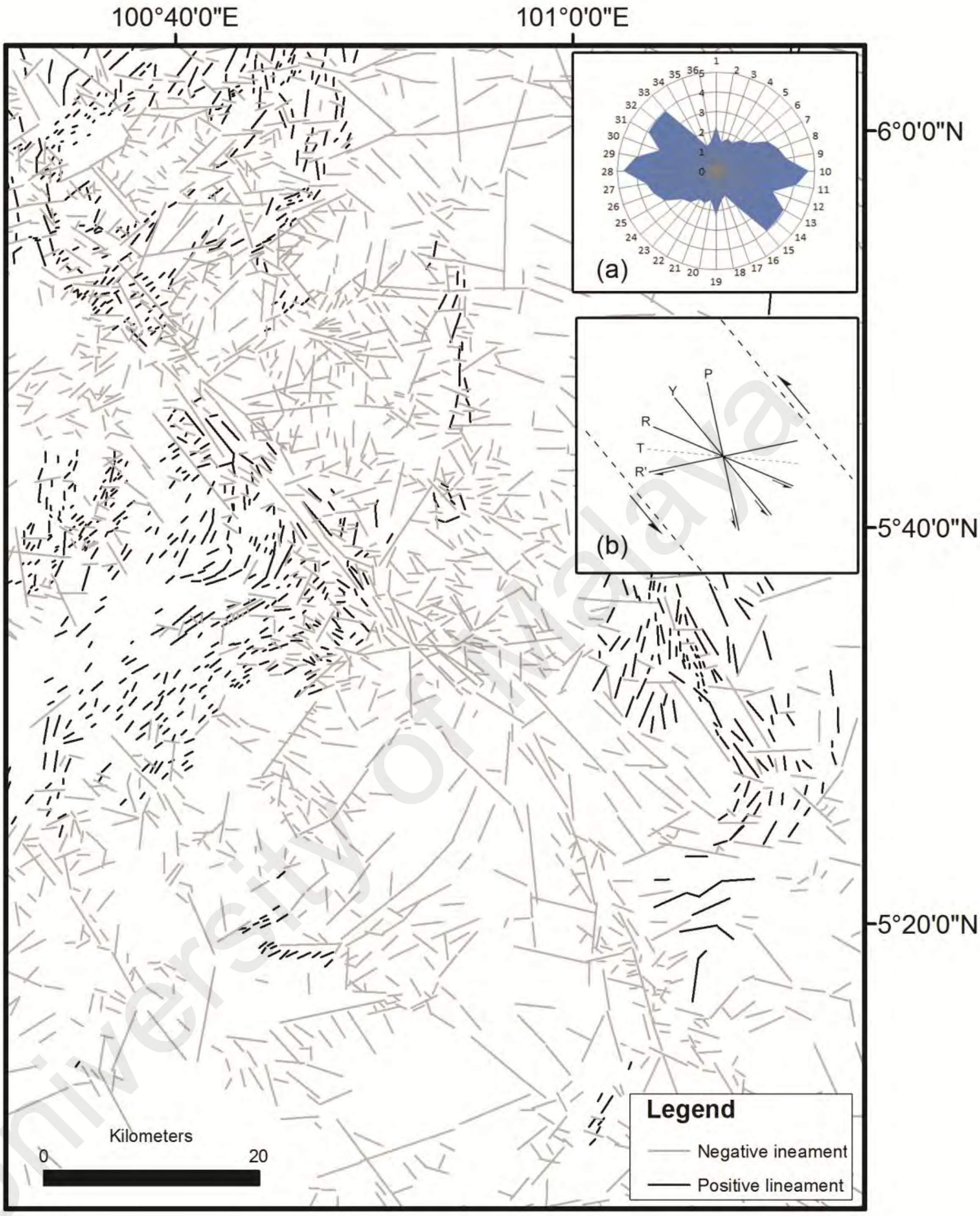

Figure 3.13: Lineament map and Riedel Shear interpretation of lineaments. (a) Rose diagram of lineament; and (b) Riedel Shear component

Table 3.3: Interpretation of simple shear model for Bok Bak Fault Zone, with corresponding shears and faults

Riedel Shear	Orientation	Fault or related structures
Principal shear / Y shear	320°	NW sinistral Bok Bak Fault, NW shear zone
R-shear	305°	WNW sinistral faults
P-shear	335°	NNW to NW sinistral faults
R'-shear	065°	NE-SW dextral faults
Shortening axis	095°	E-W normal faults

resulting structures produced by shearing. The Bok Bak Fault one could be interpreted as undergoing a sinistral simple shearing, with NW-SE lineaments prevalent in most rock units representing major trace of the fault zone.

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CHAPTER 4: DUCTILE DEFORMATION

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4.1 Introduction

Granitic rocks along the Bok Bak fault have been subjected to ductile shearing, resulting in sheared granite and mylonite observed in the field. Very few studies have noted on the occurrence of these rocks (e.g. Abdul Majid, 1987; Teoh, 1992, Abdullah, 1993). Ductile shear zones have not been found in sedimentary rocks, although they have been report of shearing of pyroclastic rock unit along the fault zone in Perak (Jones, 1970), as well as mylonite in metasedimentary rocks (Ulfa et al., 2012). Detailed field and microstructural studies of these faults rocks were lacking, leaving the kinematic and condition of the ductile deformation of the Bok Bak Fault unclear.

In this study, several shear zones in the field were identified and mapped, with petrography and microstructural study of oriented samples carried out in determining the nature of the ductile deformation phase. Interpretation of the kinematic and deformation condition of the ductile phase is based on deformation fabrics and structures found within the sheared rocks and minerals, and comparison with deformation experimental results from other studies.

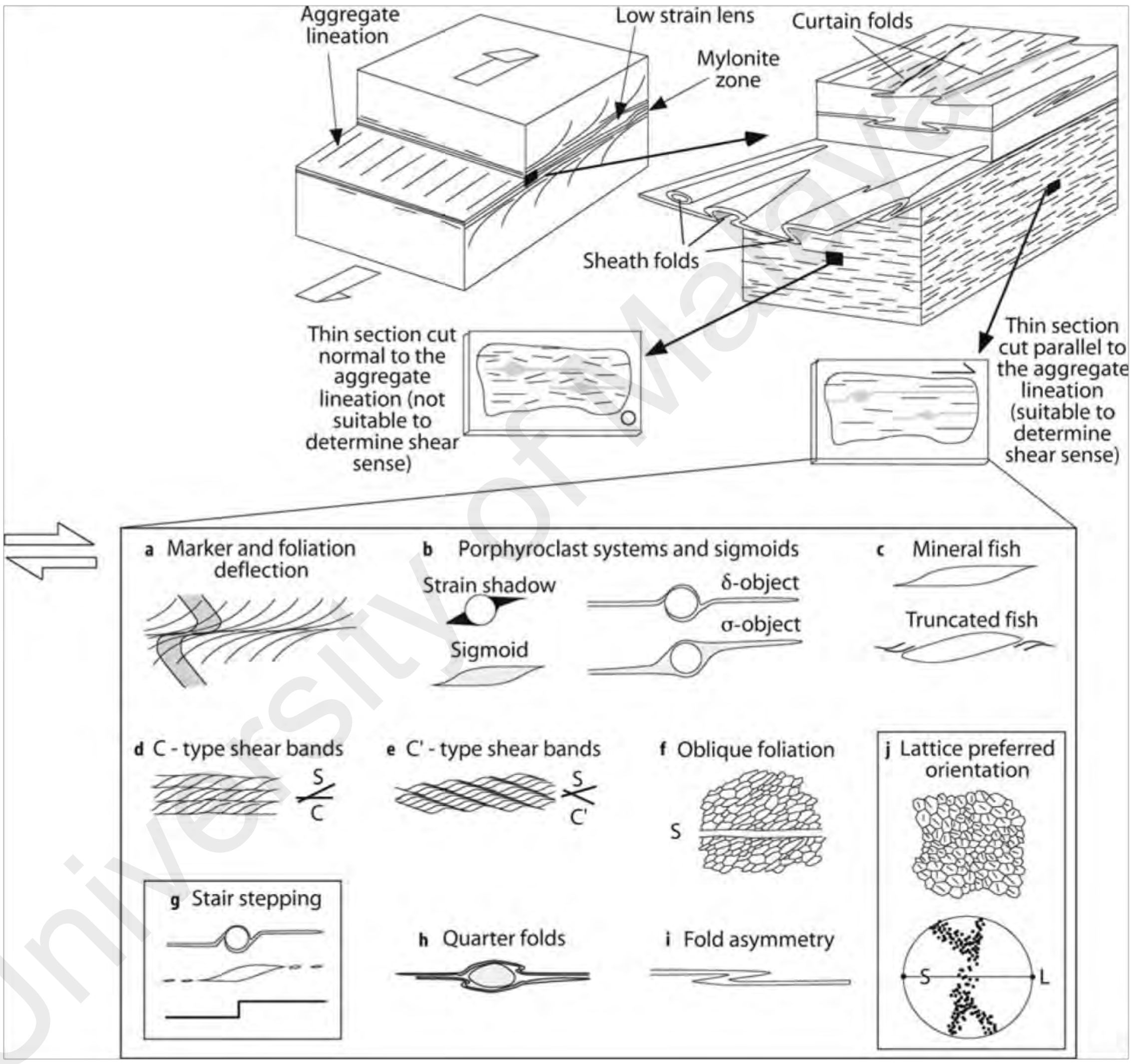


Figure 4.1: Geometry of a mylonite zone with common type of shear sense indicators shown. Thin sections are parallel to aggregate lineation. Sense of shear is dextral. (Passchier and Trouw, 1996)

4.2 Shear zone domain in granite

Shear zone is a zone of highly strained rocks bounded by undeformed adjacent rocks. Shear zone can be formed under different deformation condition: brittle deformation forms brittle shear zone characterized by fractures; ductile flow form ductile shear zone which contain foliation and lineation (Figure 4.1); and brittle-ductile shear zones are formed by both brittle and ductile mechanism and show evidence for both brittle and ductile deformation which indicate condition during shearing were either intermediate between ductile and brittle or changed from ductile to brittle or vice versa (Davis and Reynolds, 1996).

Rocks deformed in shear zones are usually referred as fault rocks (Sibson, 1977), where they are subjected to different classifications by various authors, most commonly classified by texture of the fault rocks (e.g. Sibson, 1977; Wise et al., 1984). Mylonite are fault rocks formed under ductile shearing, and are commonly classified based on the percentage of matrix compared to the porphyroclast (Figure 4.2).

Through traverse of the study area, evidences of ductile deformation were found in the granite of Bukit Perak and Baling-Gerik (Figure 4.3). The Baling-Gerik granite particularly shows clear kinematic indicators of ductile deformation, with the formation of protomylonite and orthomylonite. The Bukit Perak granite shows mostly brittle-ductile deformation features, with mylonite overprinted by brittle features.

	Non-foliated	Foliated	
Incohesive	Fault breccia (visible fragments >30% of rock mass)		
	Fault gouge (visible fragments <30% of rock mass)	Foliated gouge	
Cohesive	Pseudotachylyte		Glass or devitrified glass
	Protocataclasite	Protomylonite	<50% (% Matrix)
	Orthocataclasite	Orthomylonite	50 - 90% (% Matrix)
	Ultracataclasite	Ultramylonite	>90% (% Matrix)
		Blastomylonite	Pronounced grain growth

Figure 4.2: Classification of fault rocks (after Sibson, 1977, Wise et al., 1984, and Woodcock and Mort, 2008). Fault gouge is classified as non-foliated and foliated by Woodcock and Mort (2008)

4.2.1 Bukit Perak shear zone domain

The granite pluton of Bukit Perak is homogenous, truncated by small amount of microgranite intrusions. Granite show typical porphyrytic megacrystic texture, with only slight difference in mineral content. The undeformed granite characterized by arrangement of large feldspar clast set in groundmass of quartz, feldspar, mica, and other accessory minerals.

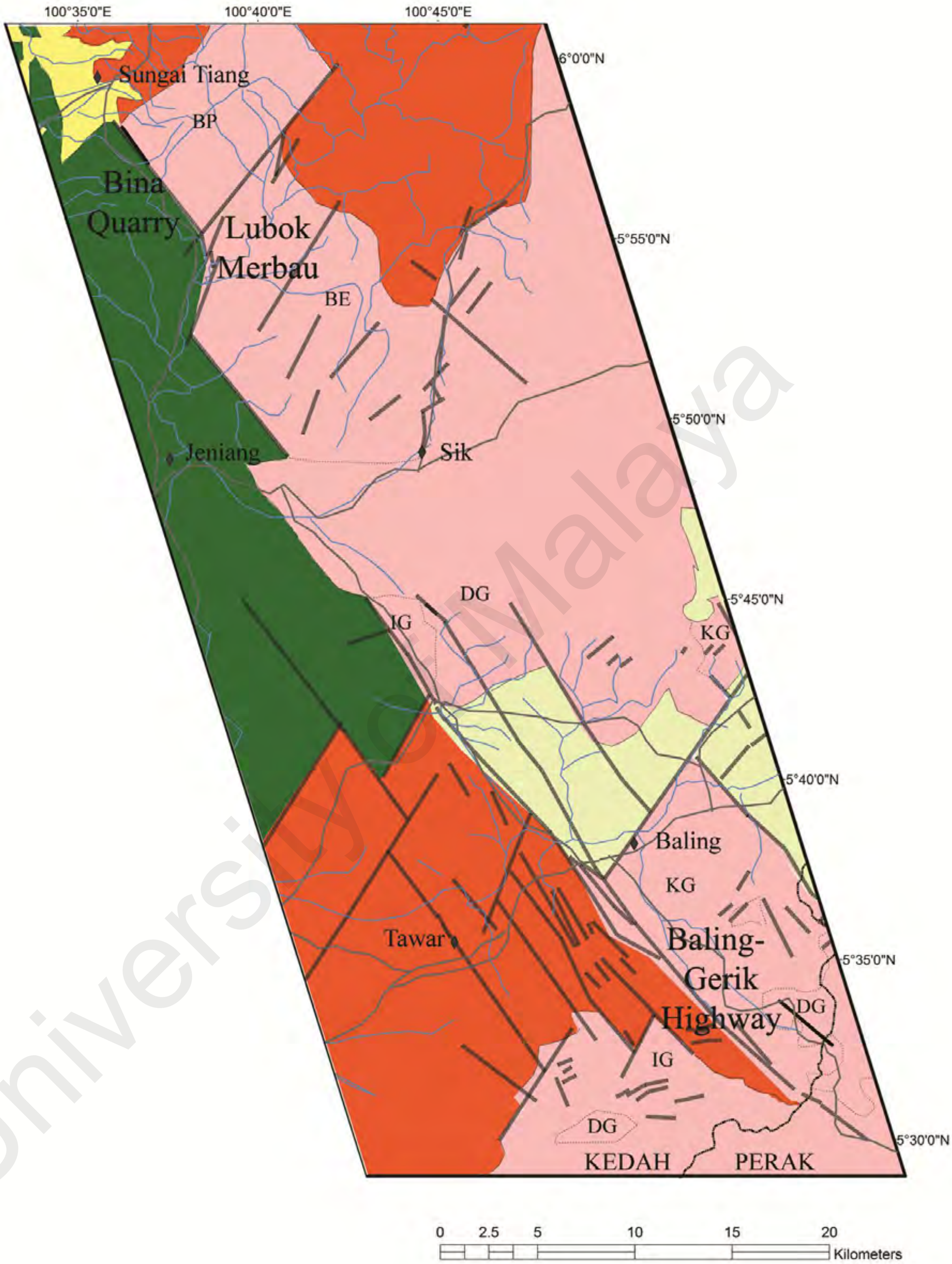


Figure 4.3: Distribution of sheared rocks along Bok Bak Fault in southern Kedah-Perak. Fault and sheared rocks mapped and based on Burton, 1972 and Teoh, 1992.

Legend

Unconsolidated sediment

Quaternary sediment

Intrusive bodies

Granite

Porphyrytic granite bodies

BE Bukit Perak Granite

BP Bukit Enggang Granite

DG Damar Granite

IG Inas Granite

KG Kupang Granite

Sedimentary rock unit

Triassic

Semanggol Formation

Shale-sandstone interbedded (rhythmite) rock unit

Ordovician-Devonian

Mahang Formation

Shale-sandstone interbedded unit

Ordovician-Devonian

Baling Formation

Metamorphosed sedimentary facies: sandstone, shale, calc-silicate, limestone

Brittle faults

Ductile shear zone

Lithological contact

Granite subdivision

State border

Major town

Major road

River

Figure 4.3, continued

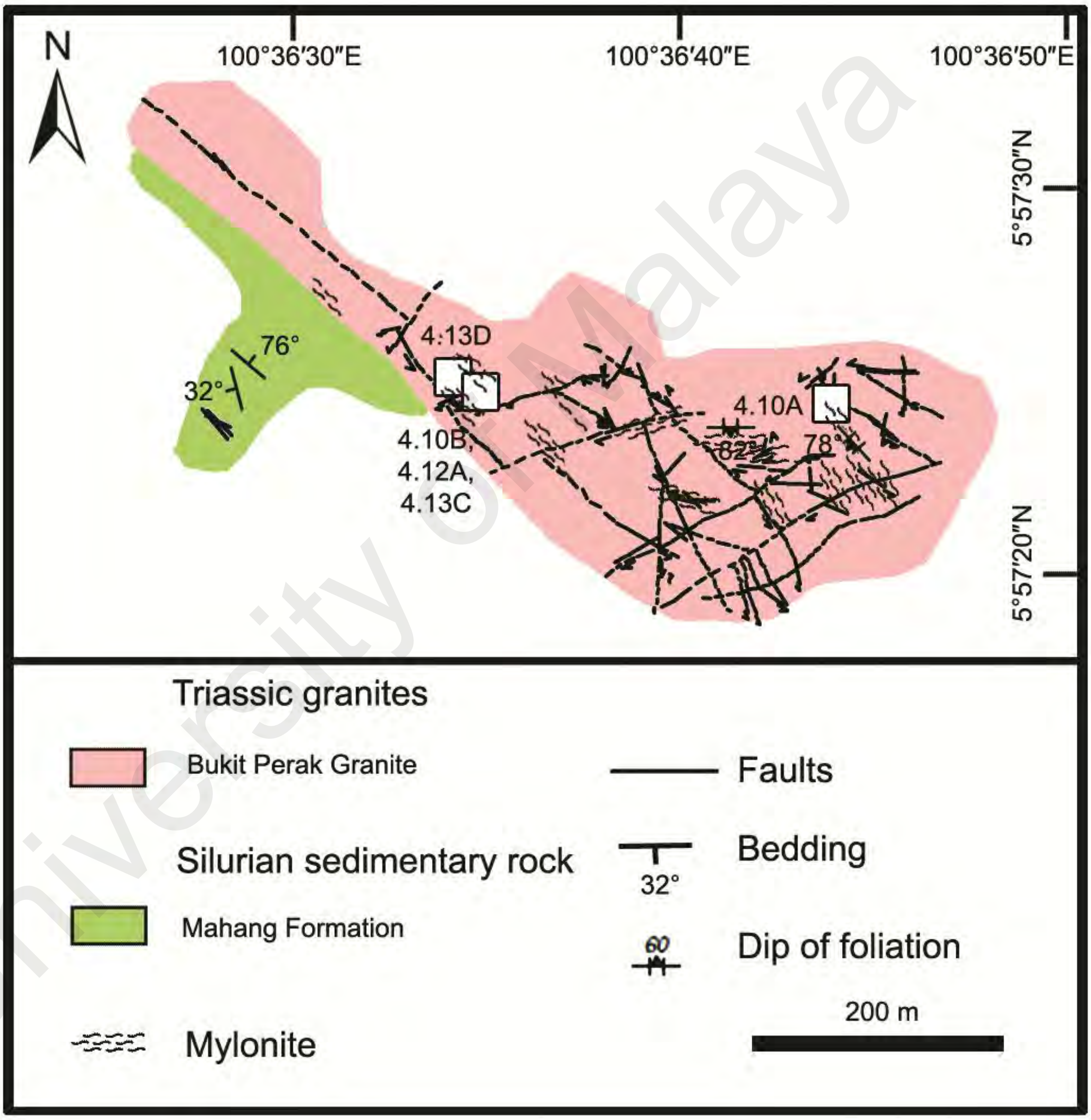


Figure 4.4: Mapped shear zone in Bina Quarry. Location of figures for samples is indicated by squares.

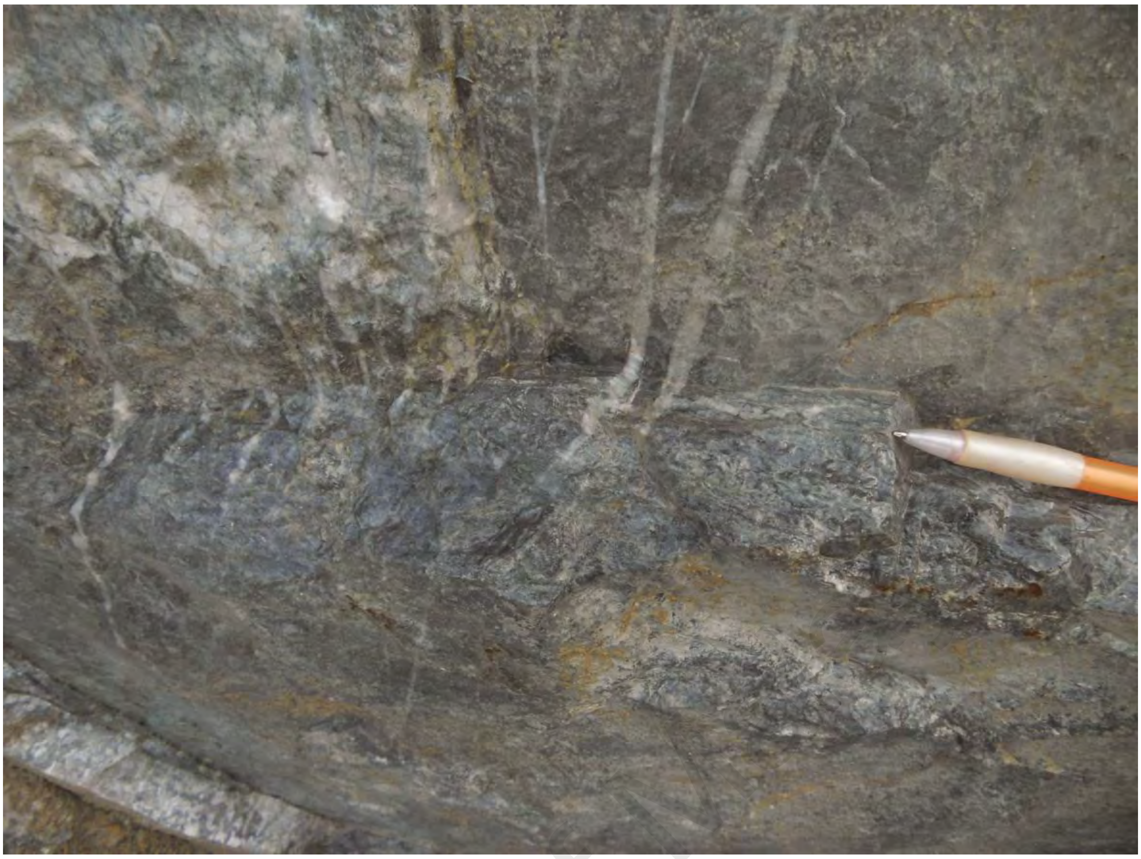


Figure 4.5: En echelon quartz filled fracture of Bukit Perak granite. View is looking towards NE. Location: Bina Quarry. Pencil as scale.

Evidences of ductile deformation in Bukit Perak are observed at a few localities, but it is particularly well exposed at Bina Quarry (Figure 4.4). The undeformed granite shows typical porphyrytic structure of the Bukit Perak pluton, with feldspars constituting the clast and the matrix consisting of quartz, alkali feldspar, plagioclase and biotite. Primary magmatic foliation is defined by arrangement of euhedral feldspar in matrix. Some of the feldspar foliation shows parallelism with trend of brittle faults which cuts the granite, but these were not taken as evidences of synplutonic deformation due to absence of ductile deformation in the matrix of the foliated granite.

Mylonitized granite is identified by dark greenish colour, and development of finer, more pronounced foliation. The deformed granite show overprinting of brittle deformation in form of fractures and slickensided surface of faults. The presence of zones of en echelon quartz filled fracture in Bina Quarry points to the occurrence of brittle-ductile deformation phase (Figure 4.5). Majority of the mylonite could be classified as protomylonite (Figure 4.2). The mylonite form zones of a few metre in thickness, which are cut by brittle faults and fractures.

Evidence of ductile deformation is also found in several small localities at the southern part of Bukit Perak pluton. Sheared granite with rotated clast and dark foliation were observed in Lubok Merbau. Clear kinematic indicators are however not present in these sheared granites, and the rock occur only in isolated outcrops.

Feldspar shows evidence of brittle deformation in thin section of the mylonite, but appear to be undeformed in hand specimens. Quartz are recrystallized in thin sections, and individual grains show evidence of deformation such as presence of undulatory extinction. Majority of the minerals were fractured, indicating that the mylonite was overprinted by brittle deformation.

4.2.2 Baling-Gerik shear zone domain

The Baling-Gerik granite shows significantly high mica content in the matrix, producing dark colour granite. In addition, the biotite forms mineral lineation across the granite, which are not to be confused with aggregate lineations that are otherwise a result of ductile shearing.

The undeformed granite of Baling-Gerik show similar porphyrytic texture to the Bukit Perak granite, with the clast consisting of feldspar and the matrix made up of quartz, alkali feldspar, plagioclase and biotite. Flow banding is observed in the granite, and compared to Bukit Perak granite there is higher occurrence of mafic xenolith and pegmatitic veining. Some of the veins appear to be subjected to shearing, where they show folding and effect of shearing.

The deformed granite form mylonites with well-developed foliation and shear bands in the field. The sigmoidal shape of the foliation, rotated clast, and S-C structure gives the sense of shear of the shear zones. Majority of the mylonite are classified as protomylonite, with some occurrence of orthomylonite. The mylonite zones are individually small – about a few metres thick – which span a broad zone of over 4 km long (Figure 4.6). The shear zones mapped does not seem to be correlated with negative lineaments plotted in Chapter 3 as they do not coincide, and it is assumed that they do not form significant zone of weakness which would otherwise be expressed as lineaments.

In the field, feldspar grains form the observable clasts of the mylonite. They were found to be undeformed in hand specimens, but in thin sections they show clear brittle deformation. Quartz grains forms the matrix, and in thin sections show clear plastic deformation and recrystallization. Biotite and muscovite forms fish structure and shear bands, clearly indicating ductile shearing process in the mylonite.

4.3 Mesoscopic structures

Lineation and foliation are major structures found in sheared granite, and along with other structures and fabrics found, provide important kinematic indicator of the Bok Bak Fault (Figure 4.7). These are used in interpreting the early stage of ductile shearing. Structures found in the field are as follow:

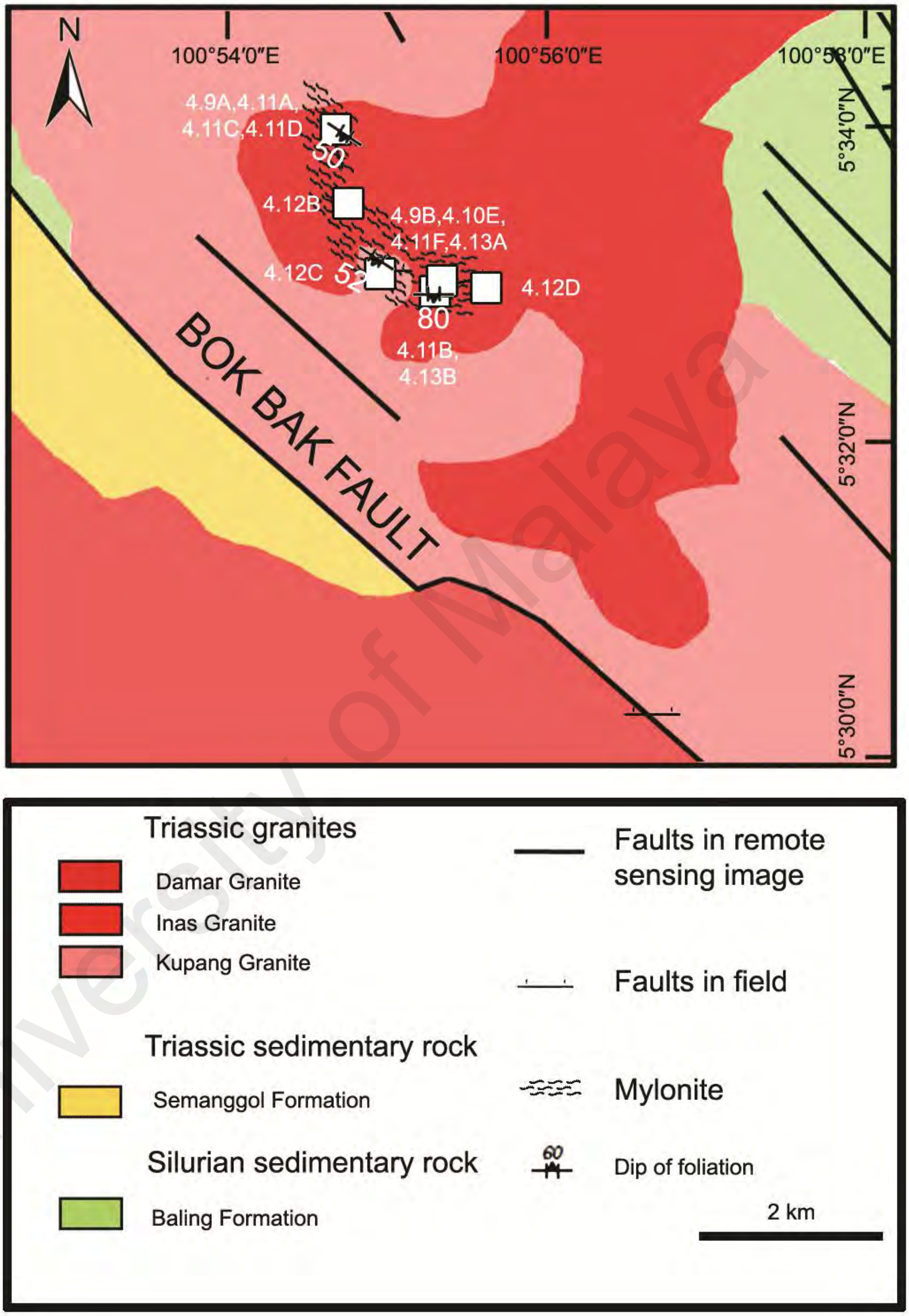


Figure 4.6: Mapped shear zone in Baling-Gerik granite. Location of figures for samples isindicated by squares. Division of granitic bodies based on Burton (1972).

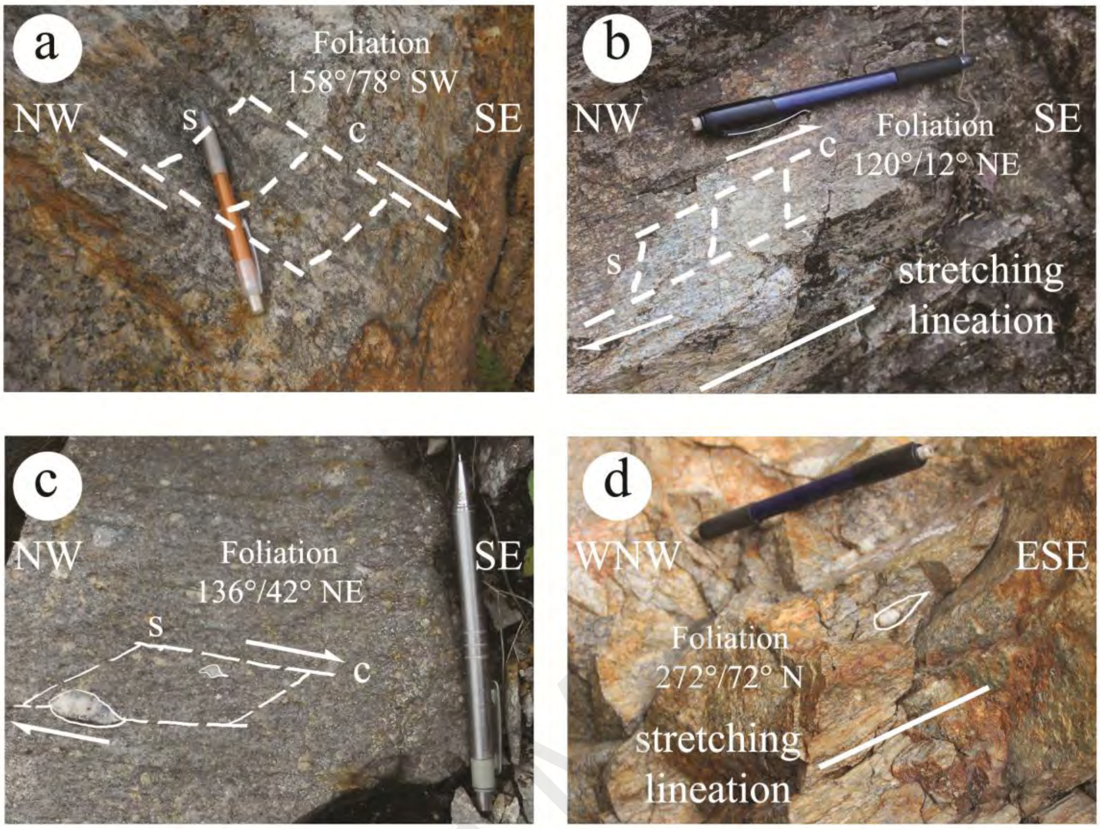


Figure 4.7: Mylonitic structure in granite along Bok Bak Fault: a) shear band in mylonite granite. View parallel to stretching lineations; b) Mylonitic foliation. View shows stretching lineations and exposed surface parallel to stretching lineation; c) S-C structure and rotated clast in mylonite. View parallel to stretching lineations; d) Narrow mylonite zone in granite with strong stretching lineations formation and large porphyroclast set in foliation. View parallel to stretching lineations. Locations: a) Bina Quarry, Bukit Perak; b) – d): K173, Baling-Gerik Highway. Pencil as scale. For locations refer to Figure 2.7.

4.3.1 Foliation

Foliated granite produced as a result of ductile shearing are readily distinguished from primary magmatic foliation in granite. The foliation is strongly penetrative in mylonite, characterized by strong preferred grain size arrangement of quartz and feldspar. The magmatic foliation, in contrast, are broadly spaced and with random arrangement of minerals.

In Bukit Perak granite, the sheared granite foliation defined by the arrangement of feldspar in matrix, shows mostly NW-SE trend in the range of 120° to 140°, dipping S and N. The Baling-Gerik fault-generated foliation strikes WNW-ESE to NW-SE, in the range of 100°-120°, generally dipping towards S. The trend of the foliation strike shows a slight swing from NW-SE to WNW-ESE southward along trace of the shear zone. The sigmoidal pattern of foliations indicate predominantly dextral strike-slip movement.

4.3.2 Mineral elongation lineation

Mineral elongation lineations are well developed on foliation planes of the mylonites, and they are defined by elongated minerals in the deformed granite (Figure 4.7d).

Figure 4.8 show the range of attitude of the stretching lineation: In Bukit Perak, the trend of the lineation is rather cluttered, but in general show sub-horizontal to gentle plunge (20°) towards northwest and southeast. In Baling-Gerik the lineation is more uniformly sub-horizontal to gently plunging (20° - 30°) to the southeast. Trend of mineral elongation lineation shows that the Bok Bak Fault undergoes predominantly strike-slip motion during ductile deformation.

4.3.3 S-C structure

S-C structures refer to the two set of penetrative foliation in mylonite: S-surface and C-surface. S-surfaces are defined by elongate mineral grains, defined by arrangement of feldspar and elongated quartz ribbons, and these form the mylonite foliation. C-surfaces

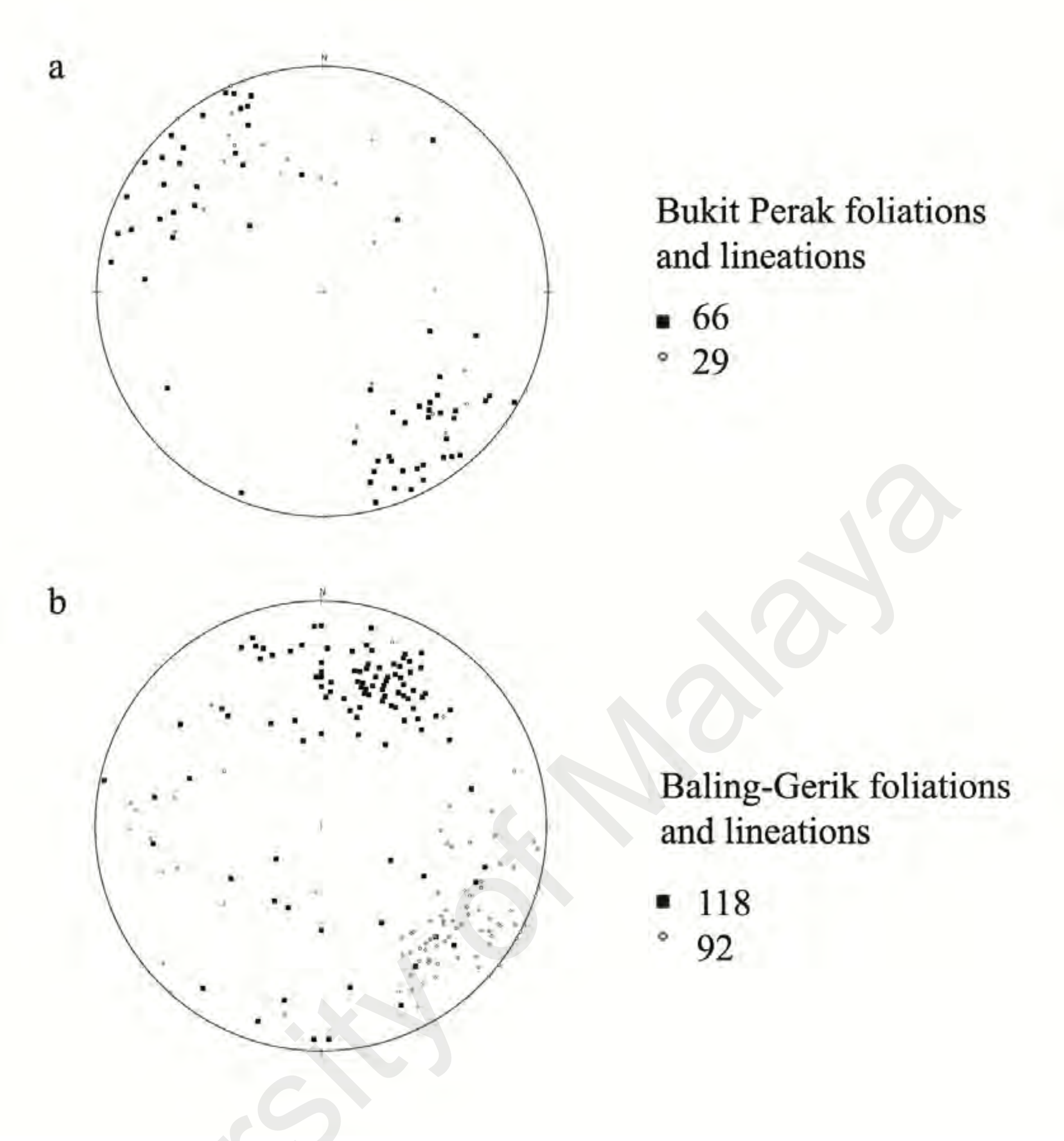


Figure 4.8: Equal area stereogram of mylonitic foliation and stretching lineations measurements along ductile shear zone of Bok Bak Fault. Stereonets show poles to ductile foliation (square) and ductile lineation (circle).

are zone of high shear strain, approximately parallel to, and having the same sense of shear, with the main shear zone (Figure 4.7b).

S-C structures are well developed in the Baling-Gerik sheared granite, and are easily identified in microscopic section of the mylonites (Figure 4.9). The structure is less well developed in the Bukit Perak sheared granite. In the field, S-C structure indicate dextal shearing of the mylonite.

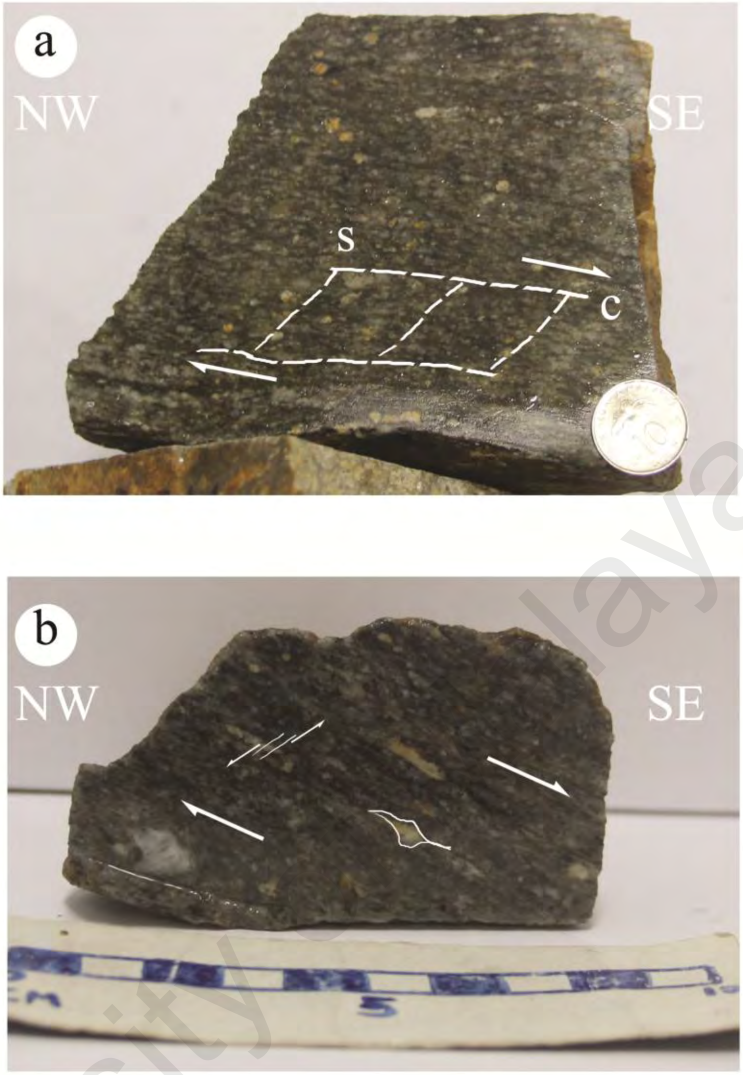


Figure 4.9: Oriented hand specimens of mylonite showing kinematic indicators: a) S-C structures; b) Mantled feldspar porphyroclast, and antithetic (sinistral) shearing in feldspar clast. Samples are cut parallel to stretching lineations. Samples location: K173, Baling-Gerik Highway. Coin as scale for a). Refer to Figure 4.6 for location of samples.

4.3.4 Rigid clasts

Rotated clast and asymmetric grain in sheared granite provide kinematic indicator alongside foliation and S-C structure. The grains are mostly feldspar set in fine grained foliation and matrix (Figure 4.7c). In some mylonite the clasts are rotated without sign of being deformed, but more commonly they are fractured, hinting at their brittle property compared to the surrounding material. Antithetic fractures were found in some of the clast, showing sense of shear opposite from overall sense of shear in the mylonite (Figure 4.9b). Along with other structures, they indicate dextral strike-slip sense of shear.

4.3.5 Deformed veins

Pegmatitic dike and quartz veins in Baling-Gerik sheared granite have been observed to show folding (Figure 2.8d). They do not provide clear kinematic indicator as other structures and fabric found in the shear zones, but their presence suggest they were formed pre-kinematic or syn-kinematic with respect to the ductile deformation.

4.4 Microstructures

Microstructural analysis was carried out on oriented thin sections of the mylonites, with thin sections cut parallel to the mylonitic lineation and normal to the main foliation, otherwise known as the vorticity profile plane, for best result of kinematic indicator (Passchier and Trouw, 1996). Microstructures found in deformed granite of the shear zone include oblique grain shape fabric, S-C fabrics, mica fish, and winged feldspar porphyroclasts, which provide important information on kinematic of deformation.

4.4.1 Oblique grain-shape fabrics

Oblique grain-shaped fabric is defined by aligned dynamically recrystallized grains oblique to the long axis of C-foliation defined by larger individual grains. Aggregates of dynamically recrystallized monomineralic aggregates such as quartz have been observed o show preferred orientation oblique to mylonitic foliation (e.g. Lister and Snoke, 1984) and this criteria is used as kinematic indicator.

In the Bok Bak Fault zone, dynamically recrystallized quartz grains are found to be aligned oblique to the C-foliation defined by band of mica and larger quartz grains (Figure 4.10a, Figure 4.11b). The microstructure is observed in most mylonite samples in both Bukit Perak and Baling-Gerik granite. Oblique grain shapes indicate dextral sense of shear in the mylonite.

4.4.2 S-C structure

Elongate quartz ribbon and mica-rich shear bands, the defining feature of S-C structures, is well observed in thin section of mylonite samples. The structure is formed parallel to stretching mineral lineation, along the vorticity profile plane. As such, they are reliable sense of shear indicator.

Mylonite from both Bukit Perak and Baling-Gerik show well developed S-C fabric, with S-fabric defined by oblique quartz arrangement, while thin band of recrystallized mica and quartz ribbons form the shear band of C-fabric (Figure 4.11a). S-C structure show consistent dextral sense of shear.

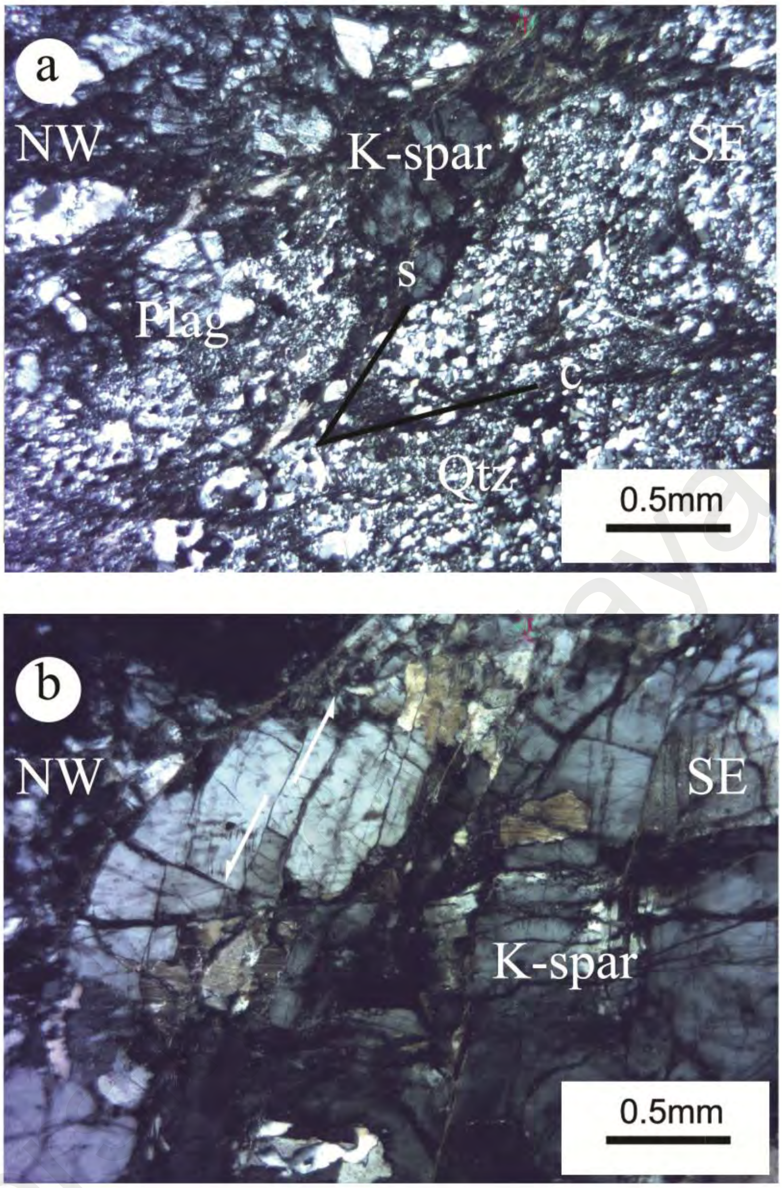


Figure 4.10: Microstructures from Bukit Perak granite (Location: Bina Quarry) indicating dextral shearing: a) shear band and oblique foliation; b) antithetic fracture in K-feldspar. Movement of fracture (sinistral) is opposite of the sense of shear in mylonite. All images under crossed nicol. Refer to Figure 4.4 for location of samples.

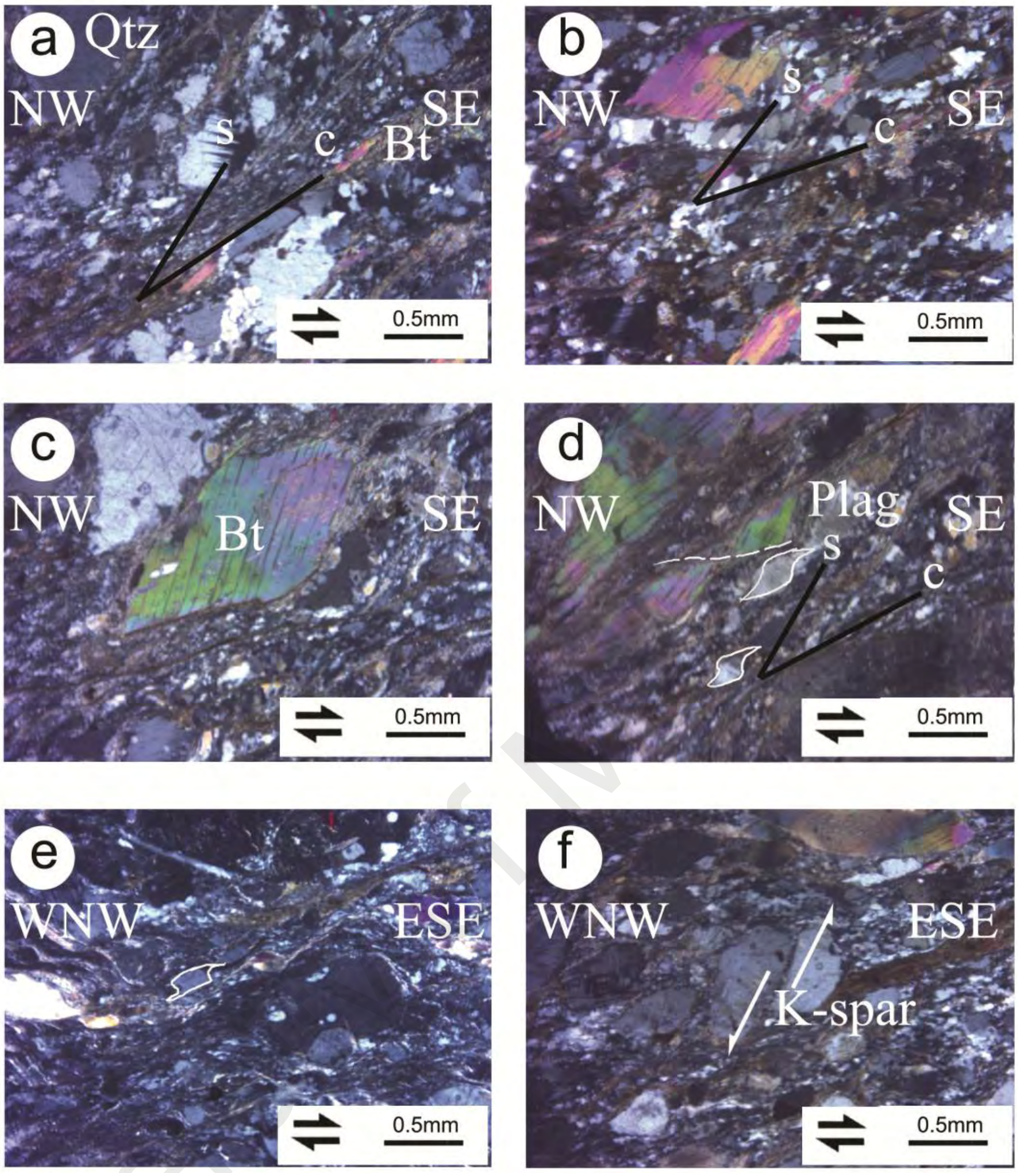


Figure 4.11: Microstructures from Baling-Gerik granite indicating WNW-ESE to NW-SE dextral shearing: a) S-C structure in mylonite. Note the trend of mica fish and feldspar porphyroclast in between C shear band; b) oblique foliation; c) Mica fish and shear bands; d) σ –type mantled feldspar porphyroclast bordered by mica fish and shear band. Note the mica fish in the centre of view being offset by shear band; e) σ –type mantled feldspar porphyroclast in mylonite; f), Antithetic fracture in K-feldspar: movement of fracture (sinistral) is opposite of the sense of shear in mylonite. All images under crossed nicol. Refer to Figure 4.6 for location of samples.

4.4.3 Mineral fish

Mica in mylonite commonly exhibit lens shaped with strong preferred arrangement to the foliation, and this structure is referred as mica fish. Commonly trails of the mica fragment extend into the matrix from the tips of isolated mica fish (Lister and Snoke, 1984), with well defined stair stepping, and are reliable sense of shear indicator. Both biotite and muscovite form the fish structure.

Mica fish are observed in the Baling-Gerik sheared granite, and are commonly arranged between C-foliation shear bands (Figure 4.11c). They indicate dextral sense of shear for the ductile shear zone.

4.4.4 Mantled porphyroclast

Mantled porphyroclast are structures that consist of central single crystal and fine-grained mantle of the same mineral. Fine grained mantle can be deformed into wings that extend on both sides of the porphyroclast parallel to the shape preferred orientation of mylonite, and are important for sense of shear determination in high strain zones (Lister and Snoke, 1984; Passchier and Simpson, 1986). Several type of mantled porphyroclast are recognized in literatures: Θ-type mantled clasts doesn’t have wings found in other mantled porphyroclast, but have a mantle with orthorhombic symmetry; σ -type-, δ -type and complex mantled clasts have monoclinic shape symmetry (Passchier and Trouw, 1996). The wing of these porphyroclasts may lie at different elevation on both sides, referred to as stair-stepping (Lister and Snoke, 1984).

In the Bok Bak Fault shear zone, mantled porphyroclasts is well observed in outcrops along the Baling-Gerik granite (Figure 4.11d-e). Here, σ –type mantled K-feldspar porphyroclasts was observed alongside structures such as S-C structure and mica fish. They demonstrate dextral sense of shear.

4.4.5 Fractured porphyroclast

Microfaulting occur in certain feldspar grains of mylonite. Compared to other microstructure, the fragmented porphyroclasts are relatively unreliable in determining overall sense of shear (Simpson and Schmid, 1983; Passchier and Trouw, 1996).

Microfracturing of feldspar is well observed in mylonite from Bukit Perak granite (Figure 4.10b). Faulting that are antithetic to the overall sense of shear in mylonite are observed in feldspar grains. The faults are limited to individual grains and does not extend into the foliation and shear band in the mylonite.

4.5 Condition of ductile deformation

Several factors control the behavior of rocks during deformation, where the deformation process affecting individual grains. Deformation process involved depends on lithological control such as mineralogy, composition, abundance of intergranular fluid, grain size, lattice-preferred orientation, porosity and permeability, and on external control such as temperature, lithostatic pressure, differential stress, fluid pressure and externally imposed strain rate (Passchier and Trouw, 1996).

There have been almost no detailed studies on deformation condition of fault zones in the Peninsular, with a few exception (e.g. Ng, 1994), and as such the ductile deformation condition of these faults are not properly understood. By studying the microstructure of the sheared rocks, this study provides a look at the deformation condition of the ductile shearing of the Bok Bak Fault.

4.5.1 Deformation mechanism

Deformation related microstructures of deformed granites vary with changing pressure-temperature and other ambient conditions (Tullis et al., 1982). In the ductile shear zone of the Bok Bak Fault, both brittle and plastic microstructures occurs in the mylonite. Rocks along the Bok Bak Fault show deformation structures that reflect ductile and brittle deformation.

Thin sections of sample from the sheared granite are studied for petrography and microstructures study. Quartz and feldspar are the major rock forming mineral in the shear zone. There is no major difference in the deformation condition between the Bukit Perak granite and Baling-Gerik granite, and thus the observations are not separated by the two domains. A summary of the deformation of the minerals is shown in Table 4.1.

Table 4.1: Summary of deformation of mineral in ductile sheared granite

Quartz	Feldspar	Mica
Elongate to ribbon shaped recrystallized grains; no fracturing observed Exhibit bulging recrystallization (BLG) and subgrain rotation recrystallization (SGR)	Deform by fracturing and cataclastic flow Minor occurrence of σ –type mantled K-feldspar porphyroclasts and recrystallization	Show kinking and folding Formation of mica fish (commonly in muscovite) Form shear band (C-surface)

4.5.1.1 Quartz

Recrystallized quartz is predominant in all mylonite samples (Figure 4.12). Crystal plastic deformation evidences in quartz are abundant, with formation of sub-grain, deformation bands, and core-mantle structures. Quartz in mylonite are commonly stretched into lenses and quartz ribbons. Commonly the quartz exhibit deformation lamellae and undulatory extinction. Microfracturing is uncommon in quartz grains.

Recrystallization of quartz occur through bulging (BLG) recrystallization and subgrain rotation (SGR) recrystallization. In Baling-Gerik, certain pegmatite dikes exhibit extensive recrystallization of quartz, with quartz exhibiting SGR recrystallization and formation of quartz ribbons (Figure 4.12d).

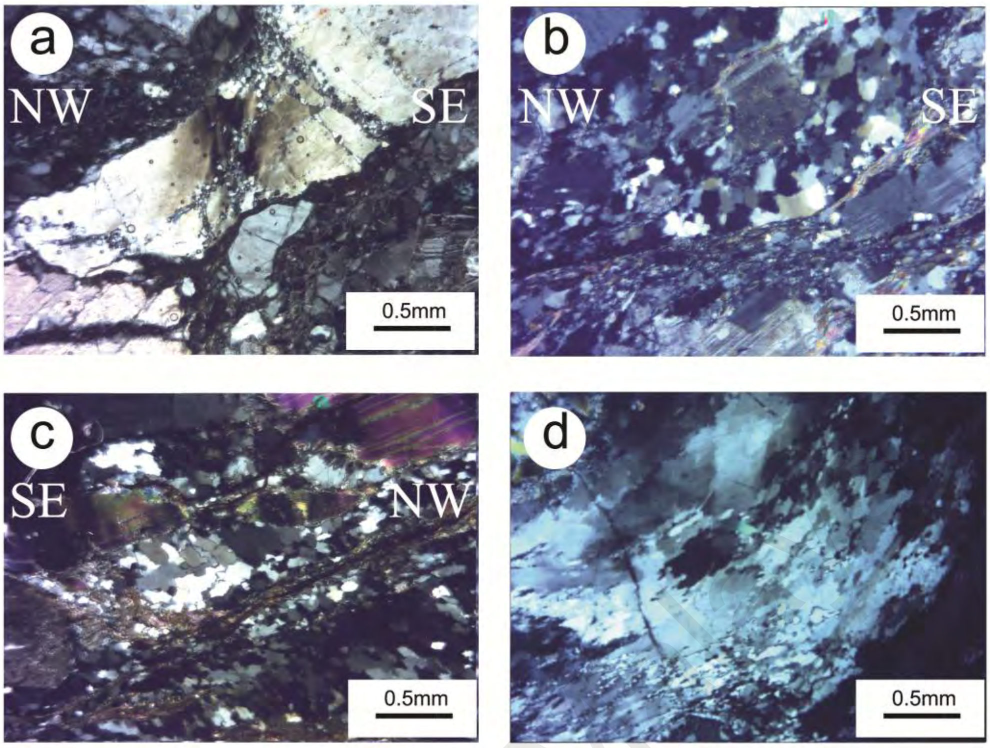


Figure 4.12: Microstructure showing deformation of quartz: a) Quartz with undulatory extinction (centre) transected by new grains formed by bulging (BLG) recrystallization; b) Dynamically recrystallized quartz formed through subgrain rotation (SGR) recrystallization; c) Quartz with BLG recrystallization occurring adjacent to grains undergoing SGR recrystallization; d) Polycrystalline quartz in pegmatitic dike developed primarily through SGR recrystallization. Samples locations: a) Bina Quarry; b) – d): K173, Baling-Gerik Highway. All images under crossed nicol. Refer to Figure 4.4 & 4.6 for location of samples.

4.5.1.2 Feldspar

Both K-feldspar and plagioclase form the porphyroclast, which are commonly fractured into smaller grains between quartz ribbons (Figure 4.13). Although both feldspar show similar microstructures, there are significant differences. While both exhibit brittle features through fracturing, K-feldspar have been found to form mantled porphyroclast structure, with formation of wings and stair-stepping structure. Deformed K-feldspar have been rotated and are aligned to the S-surface. Plagioclase exhibit mostly microfracturing and cracking with no indication of plastic deformation. Compared to quartz, recrystallization in feldspar is almost absent.

K-feldspar in mylonite generally show irregular, roughly oblong shape, with some grains forming elliptical shape in response to shearing. The largest face of the rotated grains are usually aligned with the S-surfaces. Undulatory extinction are observed in the grains, but are usually weak. K-feldspar are often microfractured, with displacement along the fracturing resulting in 'book-shaped' fragments (Passchier, 1982). Displacement along the fracturing are mostly antithetic to the overall shear sense of the mylonite. Cataclastic flow are also observed in the feldspar. In Bukit Perak granite, fracturing is very dominant in the feldspar grains and other minerals, suggesting overprinting of brittle deformation on earlier ductile features. Recrystallized K-feldspar that form mantle and core porphyroclast is well observed in one outcrop in Baling-Gerik with wings structure consisting of thin band of recrystallized grains (Figure 4.13a). In other mylonite, evidence of recrystallization is not well observed.

Plagioclase shows microfracturing similar to K-feldspar, although the degree of fracturing is less intense. The grains commonly exhibit long euhedral shape, with noticeable large size (0.5 mm to 2 mm in length). Common microstructures in plagioclase are undulatory extinction, deformation twins, and kink bands. Compared to K-feldspar, plagioclase show no evident of recrystallization, with the grains retaining their shape in mylonite (Figure 4.13b).

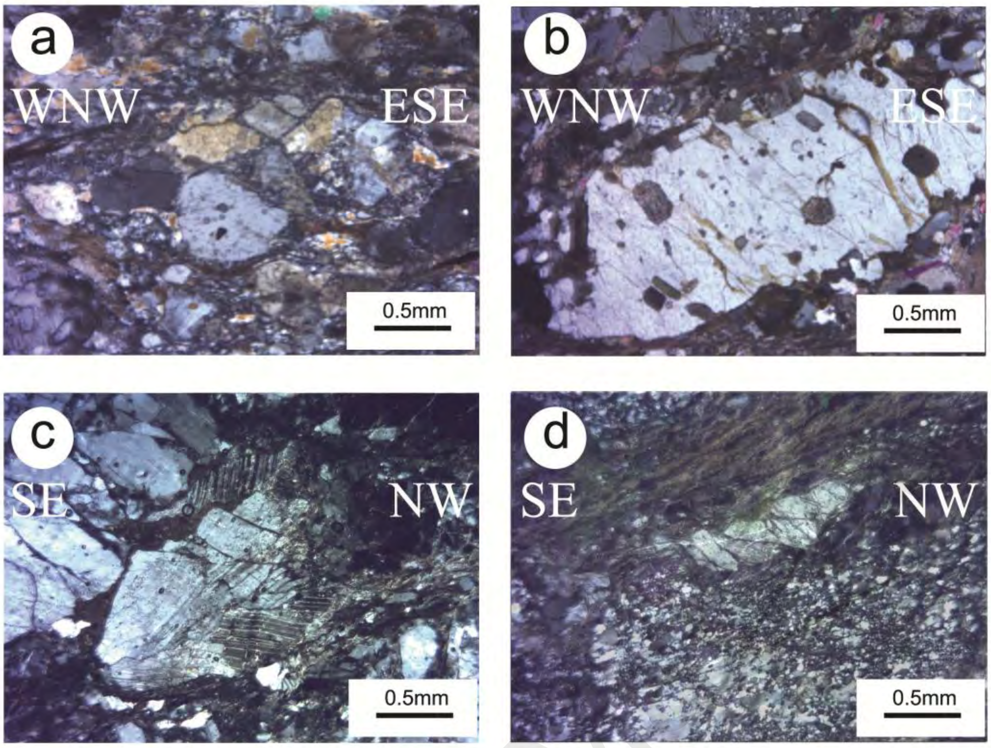


Figure 4.13: Microstructure showing deformation of feldspar: a) K-feldspar with both ductile (recrystallization of fine grains at feldspar rim) and brittle (fracturing) deformation); b) – c) Feldspar porphyroclast cut by fractures. Note twinning c); d) K-feldspar showing 'bookshelf' fracturing. Samples locations: a) – b): K173, Baling-Gerik Highway; c) – d) Bina Quarry. All images under crossed nicol. Refer to Figure 4.4 & 4.6 for location of samples.

4.5.1.3 Mica

Biotite and muscovite are the mica that makes up the constituent of the mylonite. In Baling-Gerik mylonite the mica are recrystallized to form lens shaped grains, otherwise known as mica fish (Figure 4.11c). Trails of the mica grain commonly extend from the tips of isolated grains into the matrix, forming the stair-stepping feature which is a reliable sense of shear indicator. Biotite are commonly kinked and folded.

Recrystallization occurs at margin of the mica and extend into the matrix, defining the C-surface in mylonite. In Bukit Perak mylonite, individual mica grains have appeared to be altered to form sericite and chlorite, but trace of C-surface is prevalent.

4.5.2 Temperature

The different deformational mechanism for the minerals in mylonite provides a key to the temperature of the ductile deformation of the Bok Bak Fault. Studies on experimental and naturally deformed rocks have led to the understanding of the relationship between intracrystalline microstructure for quartz and feldspar and their deformation temperatures (e.g. Tullis et al., 1985; Simpson, 1985; Passchier and Trouw, 1996). Quartz as well as mica in general show crystal-plasticity behaviour, and studies generally suggest a temperature range of 250 °C to 300 °C for the onset of crystal-plasticity. Deformation of feldspar through brittle processes happen at low temperature, below 400 °C, with the onset of recrystallization at low to medium grade condition (450 °C – 500 °C) (Pryer, 1993; Passchier and Trouw, 1996).

Quartz had undergone extensive dynamic recrystallization in all the mylonite observed, forming fine recrystallized grains. The grains are formed through BLG recrystallization and SGR recrystallization. Recrystallization of quartz are initiated at temperature of 300 °C with BLG recrystallization, with SGR recrystallization of quartz initiated at medium temperature of 400 °C (Stipp et al., 2002).

In contrast, feldspar exhibit dominant brittle behaviour through microfracturing, which include antithetically imbricate fractured feldspars in most mylonite. Evidence of plastic deformation was only observed in one outcrop in Baling-Gerik, with the formation of σ –type mantled K-feldspar porphyroclasts. Feldspar deforms through internal microfracturing with minor dislocation glide in low medium grade condition of 400 °C to 500 °C, where tapering deformation twins, bent twins, undulose extinction, deformation bands and kink bands with sharp boundaries might be present (Pryer, 1993). Mica may show kinking or layer parallel slip in the form of mica fish in brittle domain (Kanaori et al., 1991), with biotite behaving ductile at temperature above 250 °C (Stesky et al., 1974).

By comparing the contrasting behaviour of quartz, feldspar, and mica described above, the constrain for deformation temperature for ductile deformation is in the order of 300 °C to 400 °C. In this temperature range, quartz show extensive range through BLG and SGR recrystallization, with feldspar showing mainly brittle structure. The lack of recrystallization in feldspar places a lower limit for the temperature deformation below 450 °C, at which recrystallization of feldspar become significant. Presence of antithetically imbricate fracturing of 'bookshelf' microfracturing in feldspar (Passchier and Trouw, 1996) in granitic mylonite suggest deformation in low-medium grade temperature range (Pryer, 1993).

4.5.3 Metamorphic condition

While there have not been detailed thermochronologic studies on the granitic pluton cut by the Bok Bak Fault, several studies were done on metamorphic mineral assemblage of the metamorphosed sedimentary rock and igneous pluton in southern Kedah. Regional metamorphism affected the sedimentary rocks, where they are subjected to low grade regional metamorphism (Jones, 1970; Courtier, 1974; Teoh, 1992). Metamorphic rocks in Gerik exhibit greenschist facies, with a less commonly observed epidote-amphibolite facies (Jones, 1970). These rocks are subjected to a range of pressure of 0.18 Gpa to 1.2 Gpa, with temperature ranging from 400° to 700° C (Ulfa et al., 2012).

The low intensity regional metamorphism indicates a relatively low lithostatic pressure. This trend is also observed in the regional metamorphism of Malay Peninsula, where Palaeozoic rocks were metamorphosed to schists and gneisses of higher greenschist and locally low amphibolite facies (Hutchison, 2009). Although the timing of metamorphic event in the western belt is not well constrained, the widespread metamorphism event is interpreted to occur during Early to Middle Devonian (Hutchison, 1973a; Khoo and Tan, 1983).

Taking into consideration the metamorphic grades of the rocks, as well as temperature inferred for deformation from deformation microstructure in mylonite, the Bok Bak Fault must have been onset at a shallow crustal depth after the rocks were uplifted. The presence of recrystallized quartz, and other minerals such as K-feldspar, plagioclase, biotite, muscovite, and chlorite in the mylonite suggest greenschist facies condition for ductile deformation.

4.6 Summary of shear zone kinematics

The shear zones mapped in the study area were found to be formed away from lineaments plotted in remote sensing. This is taken to indicate that the mylonite zone does not form significant zone of weakness, which otherwise would be expressed as negative lineaments.

Kinematic indicators in mylonite such as foliation, S-C structures, rigid clasts, mineral fish, and mantled porphyroclasts indicate that the Bok Bak Fault had undergone WNW-ESE to NW-SE trending ductile dextral movement in its early stages. This sense of movement was not observed in remote sensing study in Chapter 3, suggesting overprinting by later brittle deformation. The quartz in mylonite show dynamic recrystallization with the formation of undulatory extinction, BLG recrystallization, and SGR recrystallization. Feldspar exhibit brittle deformation through microfracturing and cataclastic flow, and other structures such as deformation twins, kink bands, and rotated porphyroclast. Microstructure and mineral assemblage suggest that rocks along the Bok Bak Fault have undergone greenschist facies metamorphism in shallow crustal depth after the rocks were uplifted.

Kinematic indicators from mylonite consistently demonstrate top to the SE shear sense. The sub-horizontal to gently plunging stretching lineation in mylonite indicate predominantly dextral strike slip motion during ductile deformation of the Bok Bak Fault, with minor thrust movement.

CHAPTER 5: BRITTLE DEFORMATION

5.1 Introduction

The late stage brittle faulting activities in Bok Bak Fault resulted in the formation of joints, faults, and cataclasite in the field. Brittle deformation of the Bok Bak Fault occurs in both sedimentary (Ibrahim et al., 1989; Syed, 1996; Zaiton & Basir, 1999) and granitic rocks (Jones, 1970; Abdul Majid, 1987), although majority of studies have focused on faulting in sedimentary rocks. These structures have been studied by various workers, forming the basis for the interpretation of the fault zone kinematic history. Fault movements were found to be oblique slip to reverse, and overall movement along the fault zone was interpreted to be transpressional (Zaiton, 2002).

Cross-cutting relationship among the faults in the field indicate that the Bok Bak Fault have undergone several reactivation phases. Three main episodes of brittle deformation of the fault were identified from the field, and evidences for these faulting episodes and their kinematic are discussed, followed by analysis of the stress field accompanying each episodes.

5.2 Brittle deformation structures

Brittle deformation in study area is represented by joints, faults, fault rocks, and stratigraphic offset along fault planes. Angelier (1994) defined faults as discontinuities for which visible displacements have occurred, primarily parallel to the fault plane. Brittle fault rocks are formed through the fault propagation of rock, commonly along

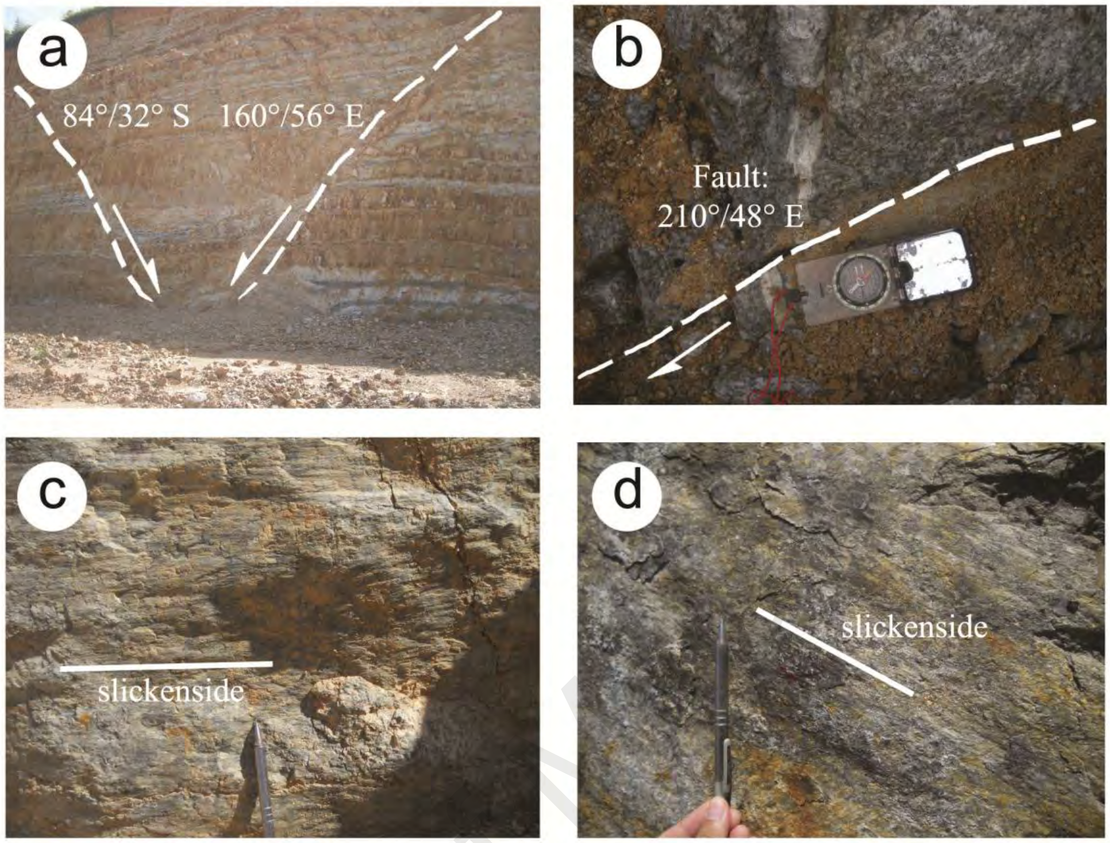


Figure 5.1: Kinematic indicator of brittle structures in Bok Bak Fault. All except b) looking into sub-vertical surface: a) Displaced of sedimentary rock unit strata of Semanggol Formation (Location: Kuala Ketil); b) displacement of quartz vein of Bukit Perak granite (Location: Pati Quarry); c) slickenside and steps on fault plane of Bukit Perak Granite, showing strike slip movement. Movement is to the right relative to the photo (Location: Pati Quarry); d) slickenside on fault plane of Bintang Hills Granite, showing normal movement (Location: Baling-Gerik Highway). b) Compass as scale; c) – d): pencil as scale. For locations refer to Figure 2.7.

older plane of weakness, and formation of a volume of brittle fault rock in a fault zone along the active fault (Passchier and Trouw, 1996). As shown in Chapter 4, brittle fault rocks could be subdivided into incohesive and cohesive type (Figure 4.1): incohesive fault rocks were grouped based on classification by Sibson (1977), and Woodcock and Mort (2008); while cohesive fault rocks were grouped based on the terminology by Wise et al. (1984), incorporating the terms from the classification by Sibson (1977).

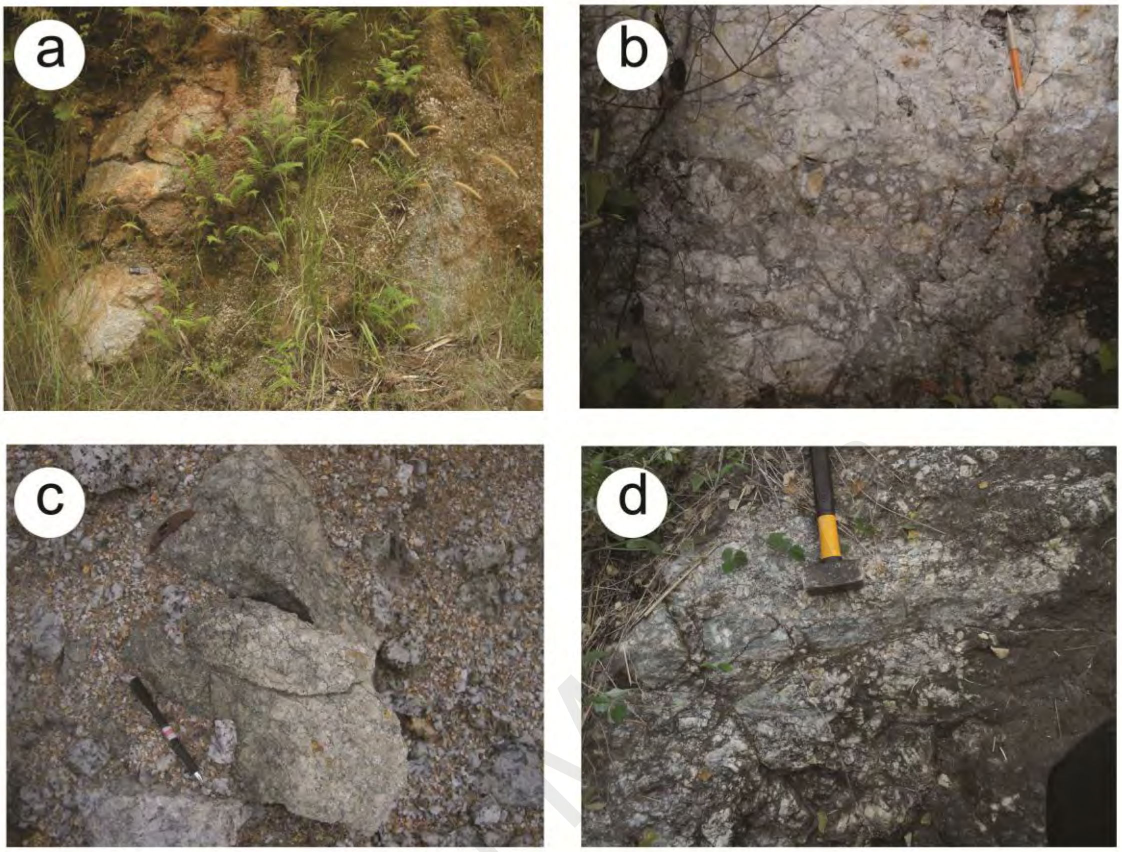


Figure 5.2: Brittle fault rocks in Bok Bak Fault: a) Fault breccia in Bukit Perak Granite (Location: Pati Quarry); b) – c) Cataclasite in granite (Location: b) Lubok Merbau; c) TAHB Quarry; d) Brittle shear band in Bintang Hills Granite (Location: Baling-Gerik Highway). a) – c) Pencil as scale; d) Hammer as scale. For locations refer to Figure 2.7.

Both fault gouge and fault breccia were observed in granitic and sedimentary rocks (Figure 5.2). Fault gouge are weathered rock along fault planes, with few large fragment isolated in matrix. Fault breccia consists of sharp angular granitic clasts set in weathered matrix. Contact with host granitic rock is usually sharp, defined by fault plane. Cataclasite are well developed in granitic rocks, where they consist of coarse poorly sorted angular clast set in finer matrix. Most of the cataclasite are categorized as protocataclasite and orthocataclasite, with the matrix percentage less than 50% and 50% - 90% respectively. Cataclasite found in the field are differentiated from fault breccia and fault gouge by their cohesive nature, and may occur in host rock without any obvious discontinuity. Compared to fault breccia, cataclasite might appear similar to undeformed host rock, although features such as fracturing and difference of colour with host rock, are indication of their brittle properties.

Striations on faults, otherwise known as slickensides, are used in defining the net slip of faults (Figure 5.1). Care is taken when determining the sense of movement from slickensides, as they commonly only show the last movement stage on the fault (Tanaka, 1992). Plunge value of slickensides are used in classification of faults, where the fault movements are described as either strike-slip, dip-slip, or combination of both (oblique slip).

Abundant joint set cut both sedimentary and granitic rock. However, they do not produce striations that are useful for kinematic analysis, and so their role in the kinematic history of the fault zone is therefore not discussed in this work.

5.3 Structural analysis

Data from the fault plane is calculated for principal directions of finite strains, and graphically determined using the program FaultKin7 (available at http://www.geo.cornell.edu/geology/faculty/RWA/programs/faultkin.html, 2016). The algorithm of the program was discussed by Marrett and Allmendinger (1990), and Allmendinger et. al (2012), and is too extensive to be discussed in the scope of this work. Several basic premises for the analysis used in this work are mentioned below:

Kinematic analysis of faults begins with graphical construction of the principal incremental shortening and extension axes for given population of faults. The pair of axes are in the 'movement plate' containing slip vector and the normal vector to the fault plane, making a 45° angle with each of the vectors (Figure 5.3). Extension (T-axis) and shortening (P-axis) axes can be found and graphically contoured (Kamb, 1959) to reveal average axial distribution of the d1 (maximum extension) and d3 (maximum shortening) axes. Bingham distribution statistic for axial data (Mardia, 1972) provides objective directional maxima of the shortening and extension axes of a fault array. The analysis calculate the maxima in a linked fashion by counting one kind of kinematic axis as positive, and the other as negative (Marrett and Allmendinger, 1990).

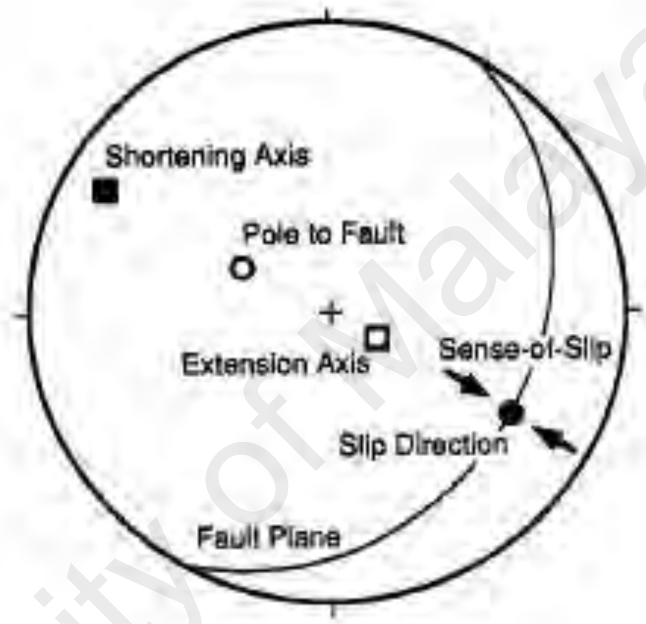


Figure 5.3: Geometry of fault-slip kinematics in lower hemisphere, equal area stereographic projection (Marrett and Allmendinger, 1990)

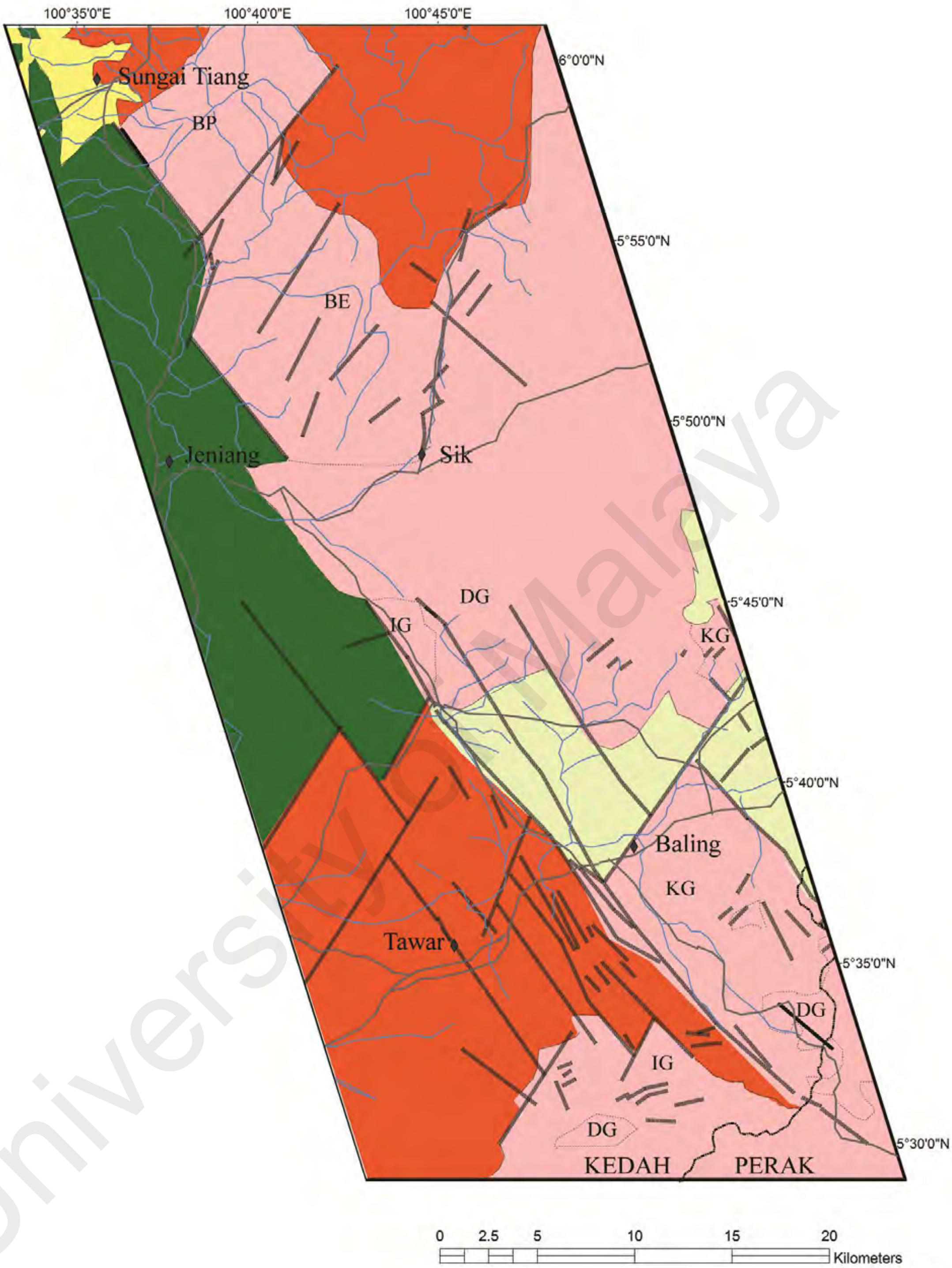
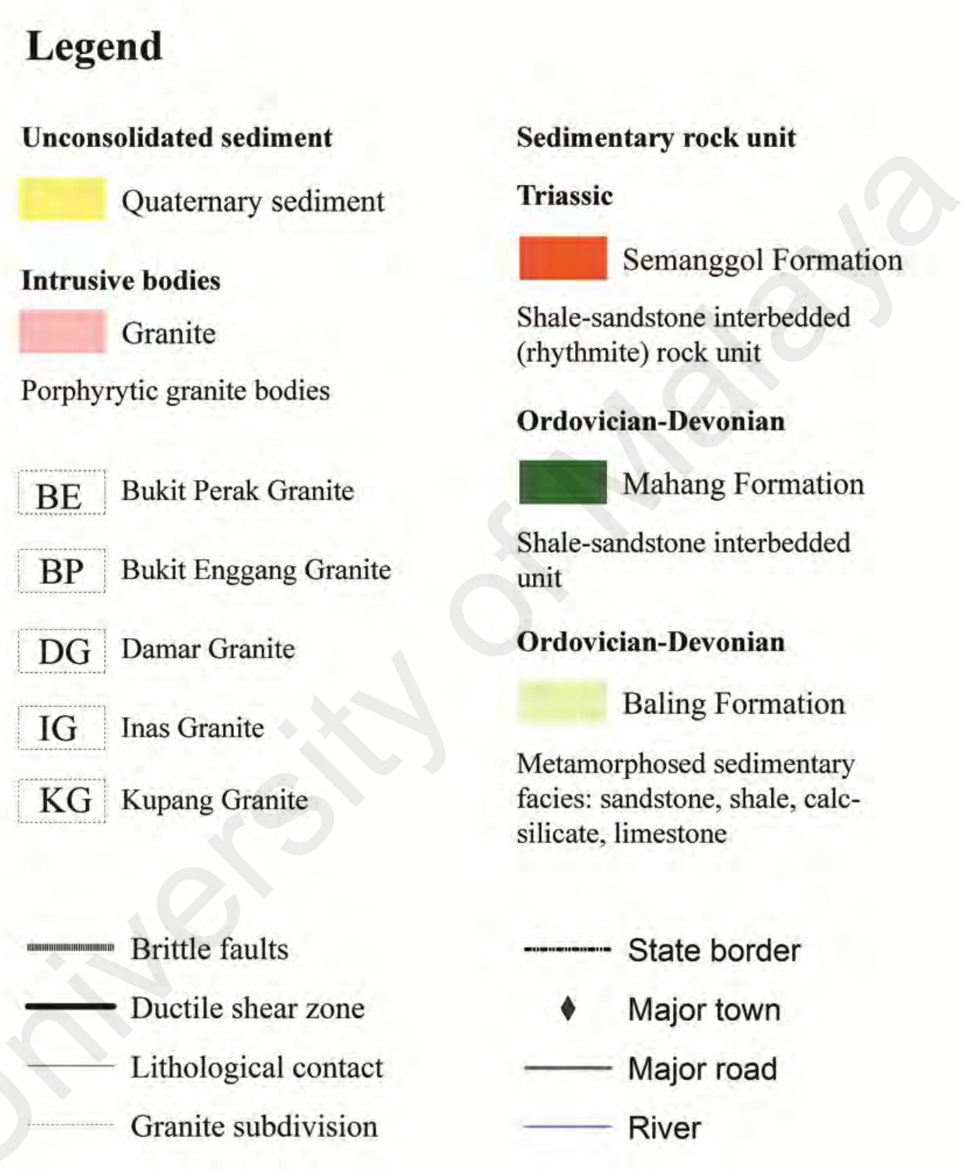


Figure 5.4: Bok Bak Fault distribution in study area. Mylonite equal area southern hemisphere stereonets show poles to ductile foliation (square) and ductile lineations (circle). D1, D2, D3 equal area southern hemisphere stereonets show poles to fault planes (square) and slickenside lineations (circle).



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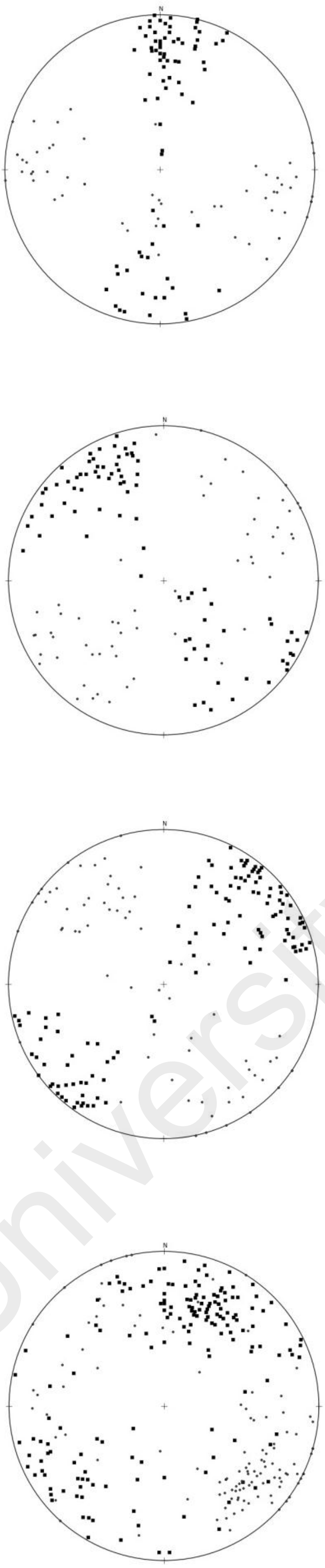

D3 Faults and slickensides

■ 85
• 60

D2 Faults and slickensides

■ 87
• 58

D1 Faults and slickensides

■ 131
• 66

Mylonite foliations and lineations

■ 184
• 121

Figure 5.4, continued

5.3.1 Transition from ductile to brittle shearing

Shear zone with combination of both ductile and brittle features were observed in Bina Quarry (Figure 5.5). These structures overprint mylonitized granite, and are in turn cut by brittle structures. The shear zone strikes around 120°, with kinematic indicator showing sinistral movement. Ductile feature dominate the shear zone: the quartz and feldspar form bands that are similar to mylonitic texture, with quartz undergoing plastic deformation. Under thin section, quartz shows extensive plastic deformation, while feldspar were subjected to heavy fracturing (Figure 5.6). The shear zones do exhibit several brittle features, with formation of en-echelon quartz veins, and sharp fault planes at the margin of the shear zone. These structures are better known as brittle-ductile shear zones, and most likely begin as ductile shear zone, but begin to develop brittle fault-like features when physical conditions changed during deformation (Davis and Reynolds, 1996).

The orientation and sense of shear of the shear zone is similar with the D1 faults discussed next. This suggests that the brittle-ductile shear zones were generated under similar deformation condition that predates D1 faults. The sinistral sense of shear reported in the mylonite of Bukit Perak reported by Abdullah (1993) is most likely this brittle-ductile shear zone.

Figure 5.5: Brittle-ductile shear zone of Bukit Perak granite. View is looking towards NW. Location: Bina Quarry. Pencil as scale.

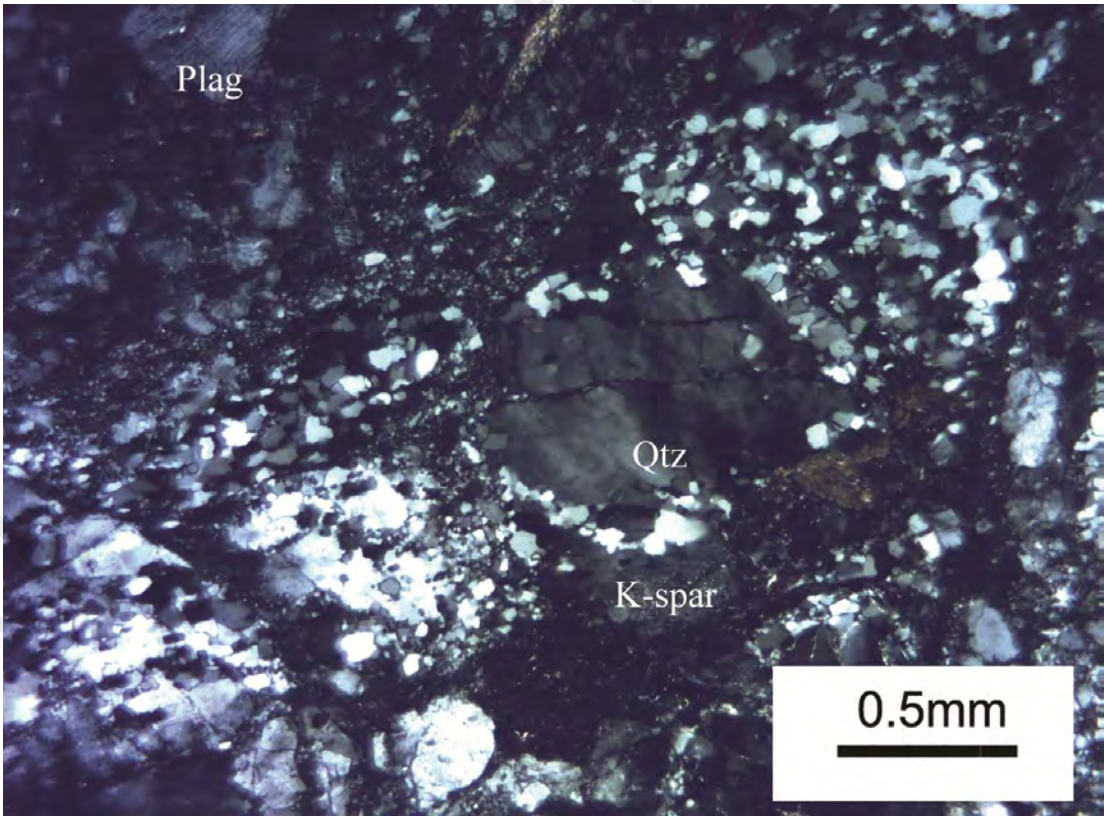

Figure 5.6: Photomicrograph of brittle-ductile shear zone rock. Location: Bina Quarry. Image under crossed nicol.

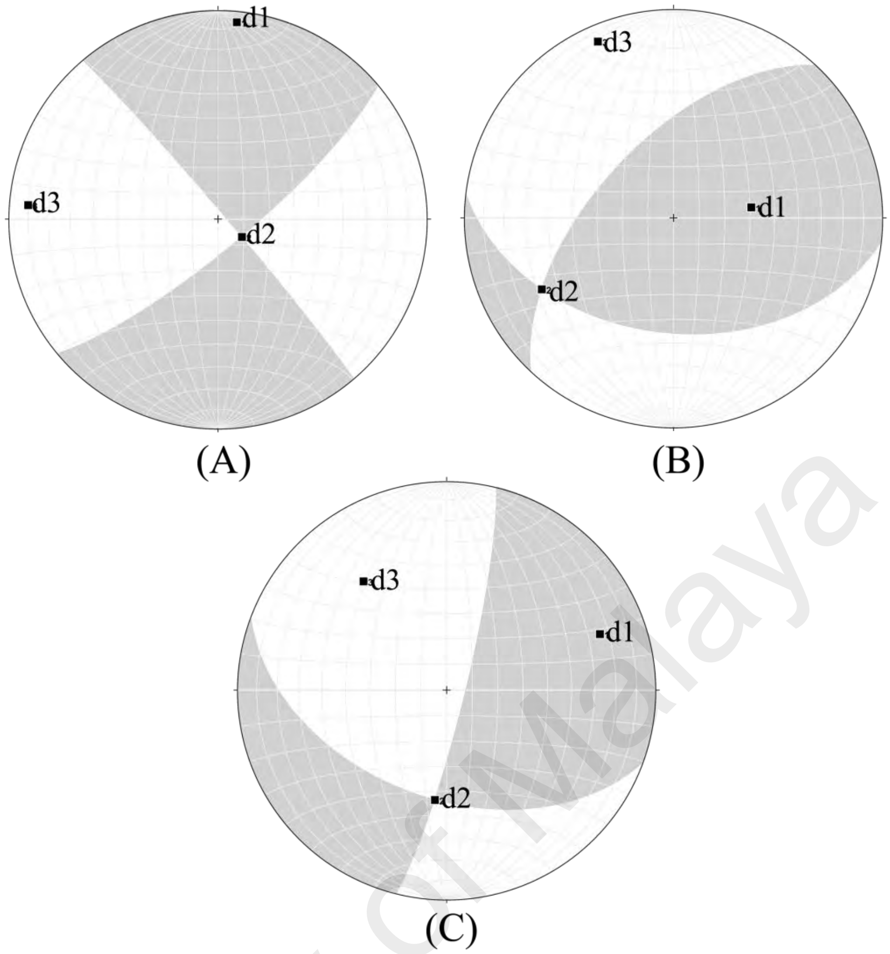

Figure 5.7 Fault plane solution of faults representing different brittle deformation episodes: (A) D1; (B) D2; (C) D3. d1: extension axis; d3: shortening axis

Table 5.1: Linked Bingham axes analysis of fault planes representing different brittle deformation episodes. d1 axis represents maximum extension, d3 axis represents maximum shortening.

Fault episode	d1axis	D2axis	d3axis	Deformation
D1	6°, 005°	79°, 127°	10°, 274°	Strike slip
D2	59°, 082°	29°, 242°	9°, 337°	Oblique slip
D3	23°, 070°	46°, 186°	35°, 323°	Oblique slip

5.3.2 D1: Sinistral oblique faulting

The period of sinistral strike-slip faulting of D1 is the most intense of the brittle deformation, forming the main trend of the Bok Bak Fault Zone which is visible in remote sensing and in the field. This period of deformation forms steeply dipping fault with orientation that range between 120° to 160° (NW-SE to NNW-SSE). Trace of the main Bok Bak Fault Zone extend up to 70 km southeastward of Baling, within a zone of almost 15 km (Raj, 1982), although there have been field reports of extension of the fault zone further northwestward. Combined with field signature of the faults reported, the total brittle length of the main Bok Bak Fault is about 215 km (Syed, 1995).

The D1 faults cut both granitic bodies and sedimentary rock unit, and follow trace of pre-existing ductile shear zone in granite (Figure 4.3). Displacement along these faults have affected the contact of neighbouring rocks on the side of the faults. Majority of the contact between sedimentary rock units and granitic bodies are defined by faults and zone of fractures, with displaced bedding and formation of tight folding in sedimentary rock unit that are adjacent to the fault zone. In remote sensing imageries, strike ridges show swerving of their strike close to trace of NW-SE lineaments (Chapter 3). This is visible in the field by similar trend of sedimentary rock unit bedding, and is taken to represent the drag effect caused by shearing along the fault

Outcrop of major faults of this episode are characterized by zones of cataclasite, fault breccia, and fault planes with slickensides. Contact between the fault rocks with undeformed host rock are typically gradual, with intensity of fracturing and fault planes decreasing away from cataclasite zones. Fault breccia are found in some of the granite outcrops, and are more recognizable from their high degree of weathering. Contact between host rock and fault breccia are usually defined by fault planes. Fault breccia is observed in Pati Quarry (Bukit Perak Granite), and TAHB Quarry (Bukit Enggang

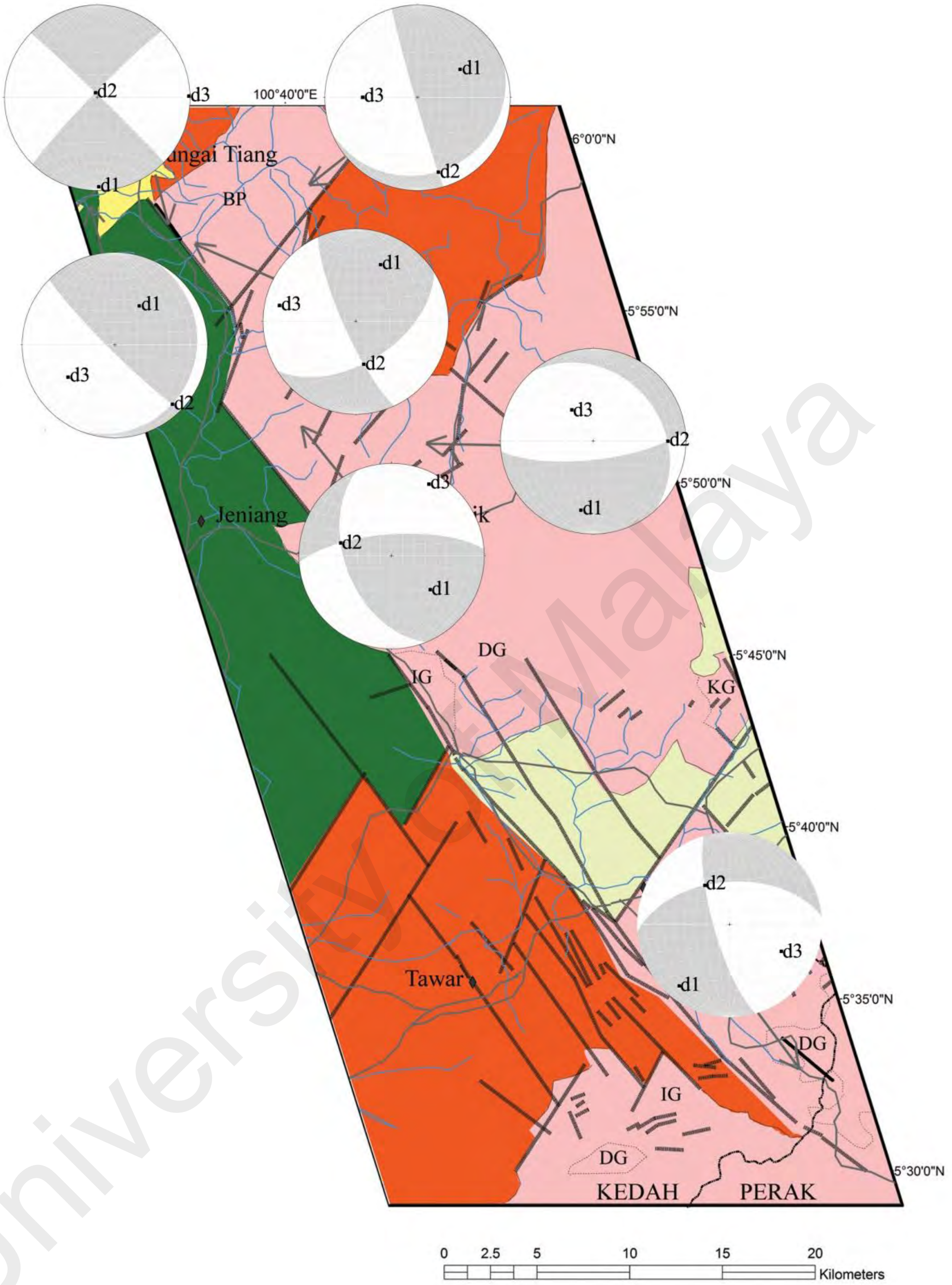

Figure 5.8: Distribution of fault plane solutions for measured D1 faults in different localities. d1: extension axis; d3: shortening axis. Refer to Figure 5.4 for details on legend of map.

Granite). Matrix of cataclasite and fault breccia are dark green to dark grey in colour. Sedimentary rock cut by D1 faults are usually weathered to form fault gouge, where well developed cataclasite were not observed. The lack of cataclastic fault rock in the sedimentary rock have been attributed to the incompetence of sedimentary strata (Teoh, 1992).

Fault planes formed during this episode of brittle deformation are marked by slickensides which indicate strike slip and oblique slip movement. The faults are steeply dipping, with dip value up to 70° and 80°, dipping towards NW and SE. Fault plane steps generally show sinistral motion, or reverse sinistral for oblique slip movement. For oblique slip movement, slickenside plunge up to 60° to NE or SW. Normal movement have however been recorded in NW faults from Semanggol Formation, as well as Bintang Hills Granite. These were taken to represent later reactivation of the faults, where condition of deformation changed from compressional to extensional.

From the sense of slip of the D1 faults, the extensional axis (d1) is inferred to be oriented N-S (005°), while shortening axis (d3) is oriented E-W (274°). The deformation experienced by the fault overall is strike slip, although individual outcrops show oblique-slip and compressional stress.

5.3.3 D2: Dextral oblique reverse faulting

The next episode of brittle faulting, D2, is a period of brittle dextral strike slip faulting. The faults formed during this episode are expressed in remote sensing and field mapping, which cuts across all rock unit and earlier faults and shear zones. The NE set faults are known as the second order strike slip faults of the Bok Bak Fault (Raj, 1982), and have been referred by several names according to their locality (e.g. the Lubok

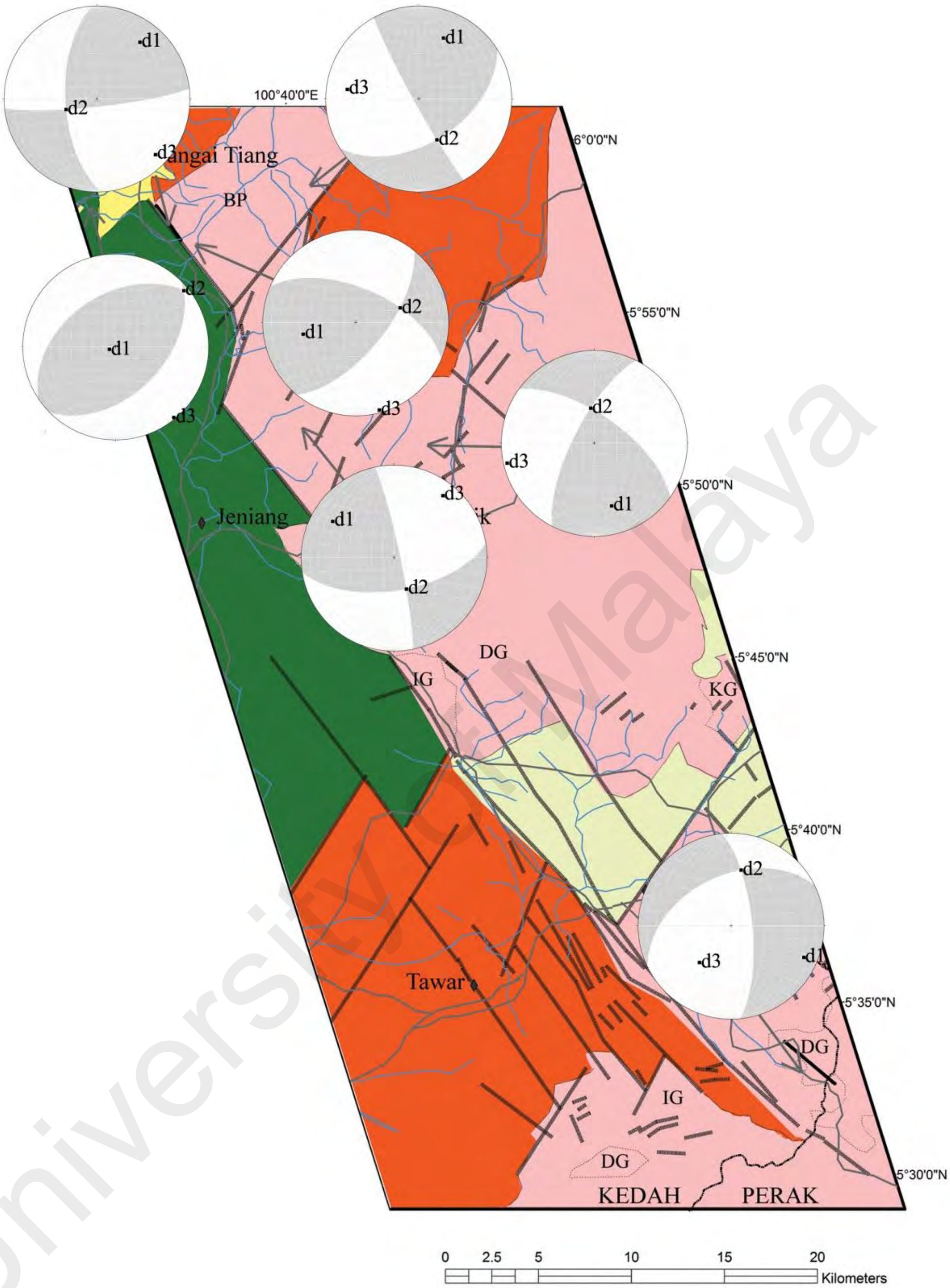

Figure 5.9: Distribution of fault plane solutions for measured D2 faults in different localities. d1: extension axis; d3: shortening axis. Refer to Figure 5.4 for details on legend of map.

Merbau Fault by Abdullah (1993)). Large quartz dyke have been found in the intersection of the NE faults with the NW faults at the southern part of Bukit Perak granite, forming outcrop of large quartz bodies (Figure 5.2b). These quartz bodies show evidence of brittle deformation, with the formation of fault and cataclasite. These quartz dikes must have therefore predates, or were formed during the D3 brittle episode.

Fault planes formed during this episode of brittle deformation are marked by slickensides which indicate both strike-slip and oblique slip movement. The faults are steeply dipping, up to 70° and 80° to the SW and NE. For oblique slip movement, slickenside plunge up to 60° to the NW or SE. Fault plane steps generally show dextral motion, or reverse dextral for oblique slip movement.

From the sense of slip of the D3 faults, the extensional axis (d1) is inferred to be oriented E-W (082°), while shortening axis (d3) is oriented NNW-SSE (337°).

5.3.4 D3: Normal faulting

The least intense of the brittle deformation, D3, is a period of normal faulting. It is expressed by outcrop scale faults which cut across older faults and shear zones. Compared to other faulting episodes, faults generated during this episode of brittle deformation do not form major topographic feature in remote sensing. E-W trending lineaments, however, do make up a majority of the plotted lineament (Chapter 3), although it is difficult to interpret whether these are related to normal faults, as no clear displacement can be observed from the lineament sets. The faults are especially prominent in Baling-Gerik, where they cut older ductile shear zones. E-W normal faults have been interpreted as late forming compared to other structures (Mustaffa, 2009b).

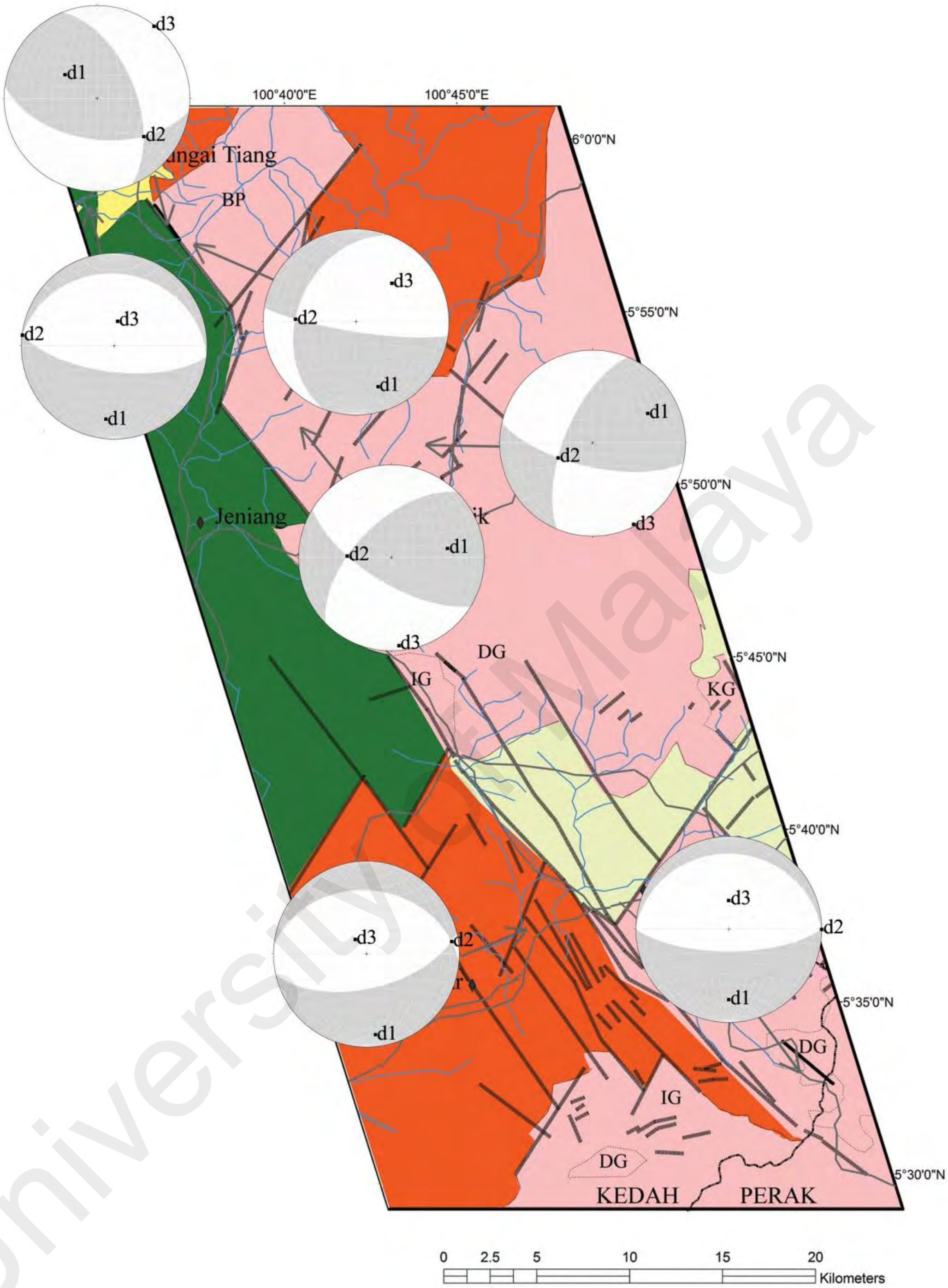

Figure 5.10: Distribution of fault plane solutions for measured D3 faults in different localities. d1: extension axis; d3: shortening axis. Refer to Figure 5.4 for details on legend of map.

The faults typically strike between 80°to 100° (E-W), with vertical to steep dips. Steeply plunging slickensides indicate normal movement in the Baling-Gerik granite and sedimentary rock unit. In the granite body of Bukit Perak Granite and Bukit Enggang Granite, E-W faults show oblique-slip component, with component of both strike slip and normal movement.

In Kuala Ketil, NW-SE and NNW-SSE faults have been found to show normal movement, alongside E-W faults which show normal movement (Figure 5.11). While a number of these faults appear to be syn-sedimentary in origin due to their limited occurrence in the sedimentary bedding, there is evidence of these faults being formed by brittle deformation: sheared rock have been found along the NW-SE faults (Figure 5.12), indicating that the normal movement along these faults are formed during brittle deformation episode. These normal movements along the NW and NNW faults could be taken as indication of the change of stress condition along the main Bok Bak Fault, from strike slip to extensional.

Cataclasite were found in association with the E-W faults in Bintang Hills granite, further supporting of these faults being formed during later episode of brittle deformation. Some of the sheared granite show greenish texture, usually forming thin bands a few centimeters in the host rock, but otherwise these cataclasite does not show obvious difference with host rock. Under microscope, the original granitic texture could still be observed, but most of the minerals are fragmented, with the quartz and feldspar clast enclosed in fine matrix (Figure 5.13).

From the sense of slip of the D3 faults, the extensional axis (d1) is inferred to be oriented ENE-WSW (070°), while shortening axis (d3) is oriented NW-SE (323°).

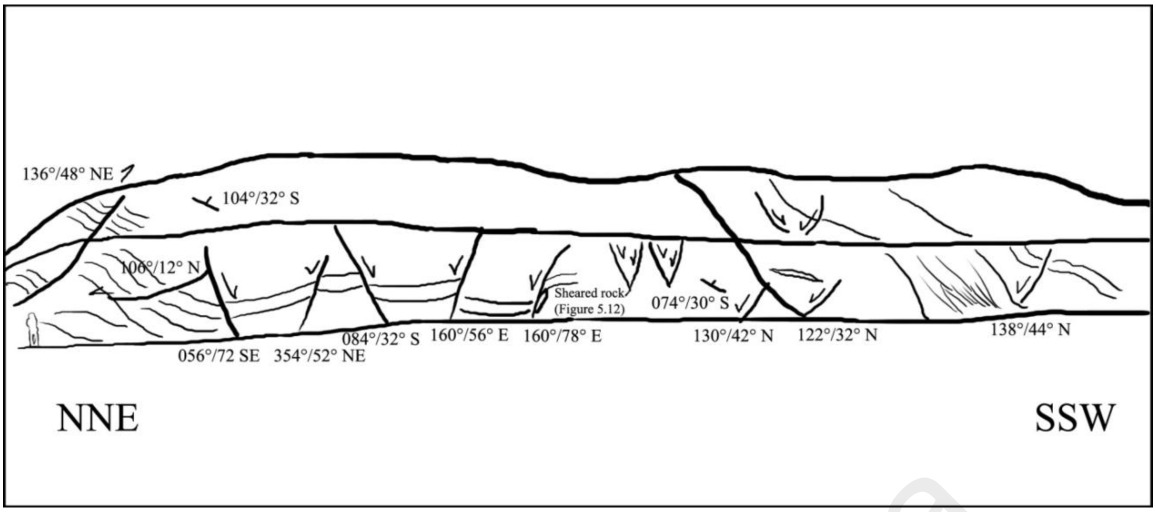

Figure 5.11: Sketch of D1 and D3 faults set, showing both reverse and normal movement. Location: Kuala Ketil. Geologist (lower left) is 1.6 m in height.

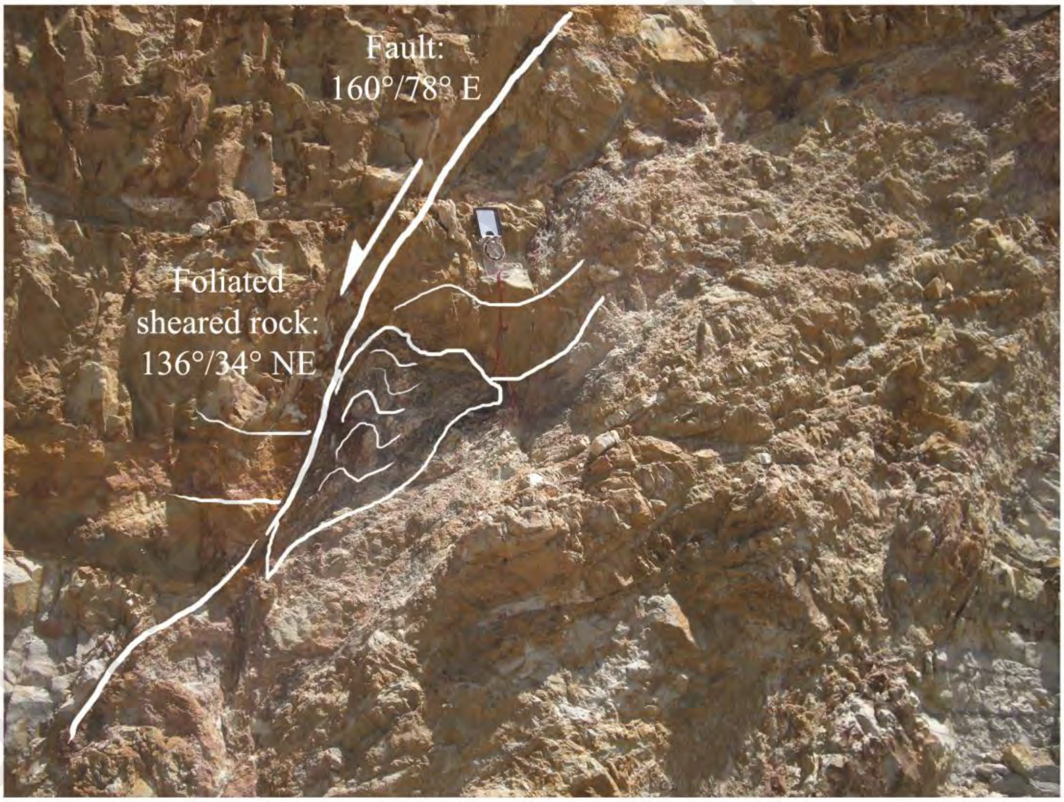

Figure 5.12: Sheared rock generated along D1 faults in Semanggol Formation, which occur in close association with D3 faults. Location: Kuala Ketil. Compass in the center of figure as scale.

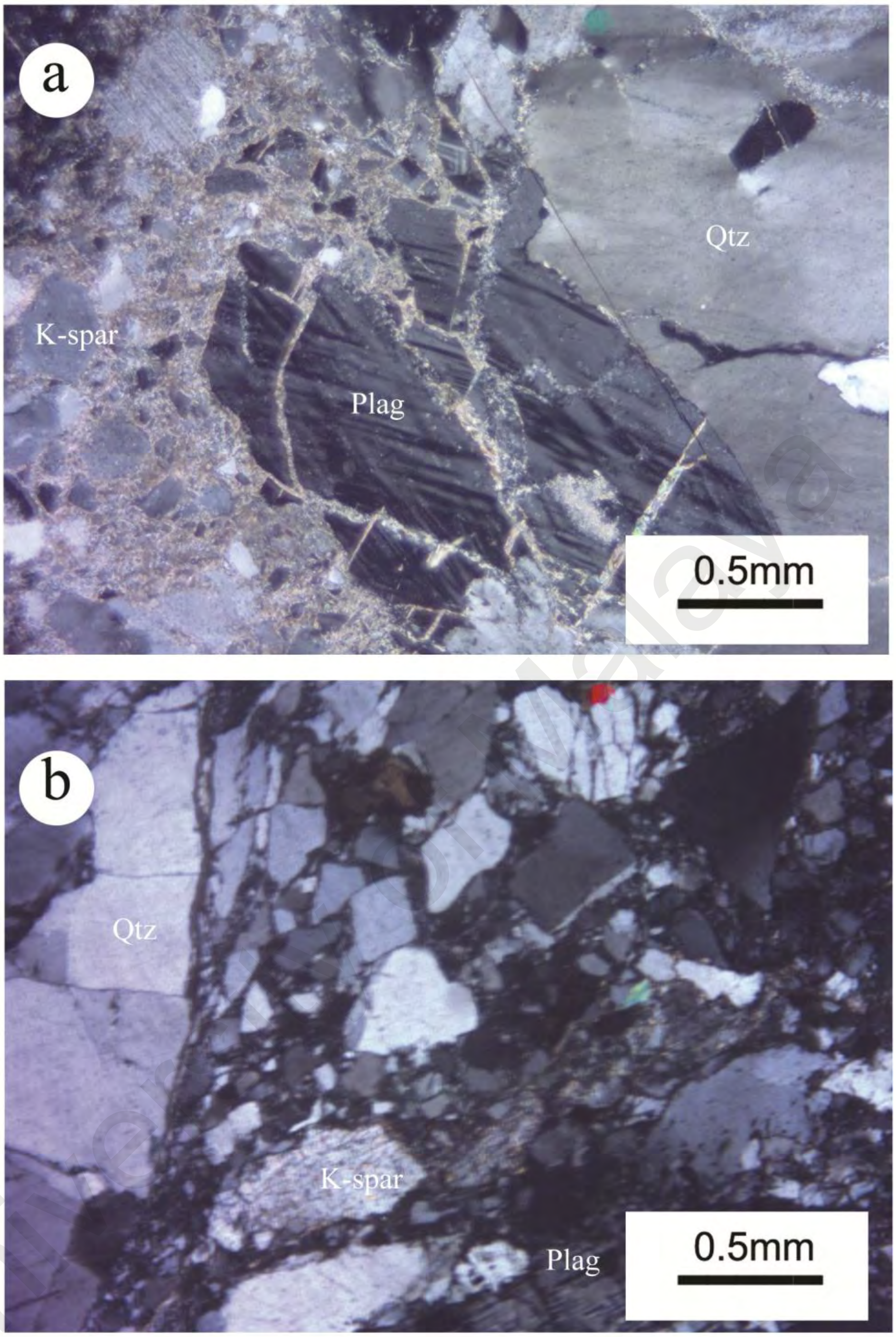

Figure 5.13: Photomicrograph of cataclasite formed in granite: a) Bukit Enggang Granite (Location: Sankojaya Quarry); b) Bintang Hills Granite (Location: Baling-Gerik highway). Images under crossed nicol. For locations refer to Figure 2.7.

5.3.5 Discussion

From crosscutting relationship, three main brittle deformation episodes were identified, following a brittle-ductile transition episode. D1 and D2 episodes are dominated by compressional stress, while D3 episode is characterized by extensional stress. From Bingham statistics, D1 episode experience compressional stress from E-W, D2 episode experience compressional stress from NNW, and D3 episode experience extensional stress from ENE.

From the kinematic analysis, between D1 and D2 episode there is a significant change of stress system, where E-W compressional stress was followed with NNW-SSE compressional stress. D2 and D3 episode appear to occur during almost similar stress system, with both episodes experiencing NNW-SSE and NW-SE compressional stress respectively. The difference however being that D3 experience major extensional stress, forming normal faults, overprinting on older strike slip and reverse movement on earlier episodes faults.

5.4 Condition of brittle deformation

Fault breccia and cataclasite show clear brittle behaviour in the minerals, with almost all minerals exhibiting fracturing (Figure 5.13). Recrystallization of quartz are found in thin section of cataclasite, but these appear to be related to hydrothermal activities rather than ductile deformation due to a lack of preferred orientation of the grains. Feldspar deform exclusively through brittle mechanism, where recrystallization of feldspar is entirely absent in cataclasite.

Brittle deformation of quartz indicate temperature of deformation less than 300 °C (Stipp et al., 2002). Sibson (1977) had estimated that the depth for formation of cataclasite at a depth of 10 to 15 km, and fault breccias at shallower level (Figure 5.14).

The brittle-ductile deformation of D1 faults show characteristic of both plastic and brittle deformation, with the formation of foliation, but brittle structures are dominant with fractures, en echelon quartz veins, and fault planes cutting the shear zone.

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5.5 Displacement of brittle fault

As all of the fault episodes show evidence of multiple reactivations, it is difficult to accurately calculate the amount of displacement associated with each individual episodes of faulting. Of the fault episodes, the NW and NE faults are ones which show clear displacement of rock units, and are visible in remote sensing imageries. Extensional period of the fault, represented by D3 faults, does not produce significant displacement of rock unit that is observable in remote sensing.

Several estimates for the amount of displacement along the Bok Bak Fault have been covered by various workers. Burton (1965), by using the lithologic boundary of the sedimentary formation in Baling, arrived at a figure of 55 km left lateral displacement for the Bok Bak Fault. Raj (1982), by restoring the continuation of Main Range Granite in southwest Kelantan and Lower Paleozoic strata in Central Perak, gave a figure of a 20 km left lateral displacement. Ibrahim et al. (1989) proposed a total of 25 left lateral movement, based on the lithofacies boundary of the Semanggol Formation, as well as considering rotational affect due to granite intrusion. Burley and Jamaluddin (1990) conducted gravity survey of Perlis, Kedah and Penang, and from steepness of granite boundaries on both side of Bok Bak Fault, interpreted a total of 30 km sinistral

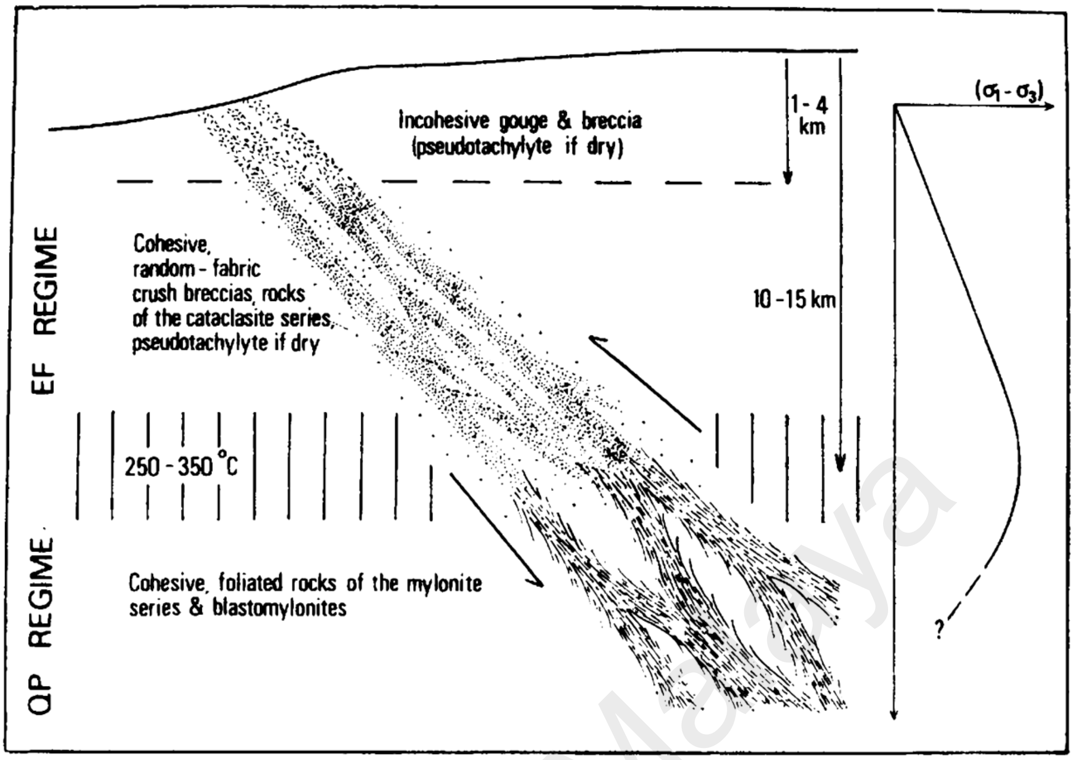

Figure 5.14: Conceptual model of a fault zone (Sibson, 1977)

displacement. Syed (1996), by using the separation between correlatable rock unit of Kubang Pasu Formation and Chuping Limestone across the fault, came to a figure of 10 km left lateral displacement.

The NE faults show clear displacement of the NW faults of the Bok Bak Fault, resulting in the en-echelon feature of the main fault strand (Figure 4.2). Teoh (1992) noted a 3 km displacement of the NW fault in Jeneri. Syed (1995) suggests a 6 km right lateral displacement along NE trending fault, based on trace of the NW Bok Bak Fault set northwest of Bukit Perak. Displacement along these faults are not as extensive as the main fault strand of the fault zone.

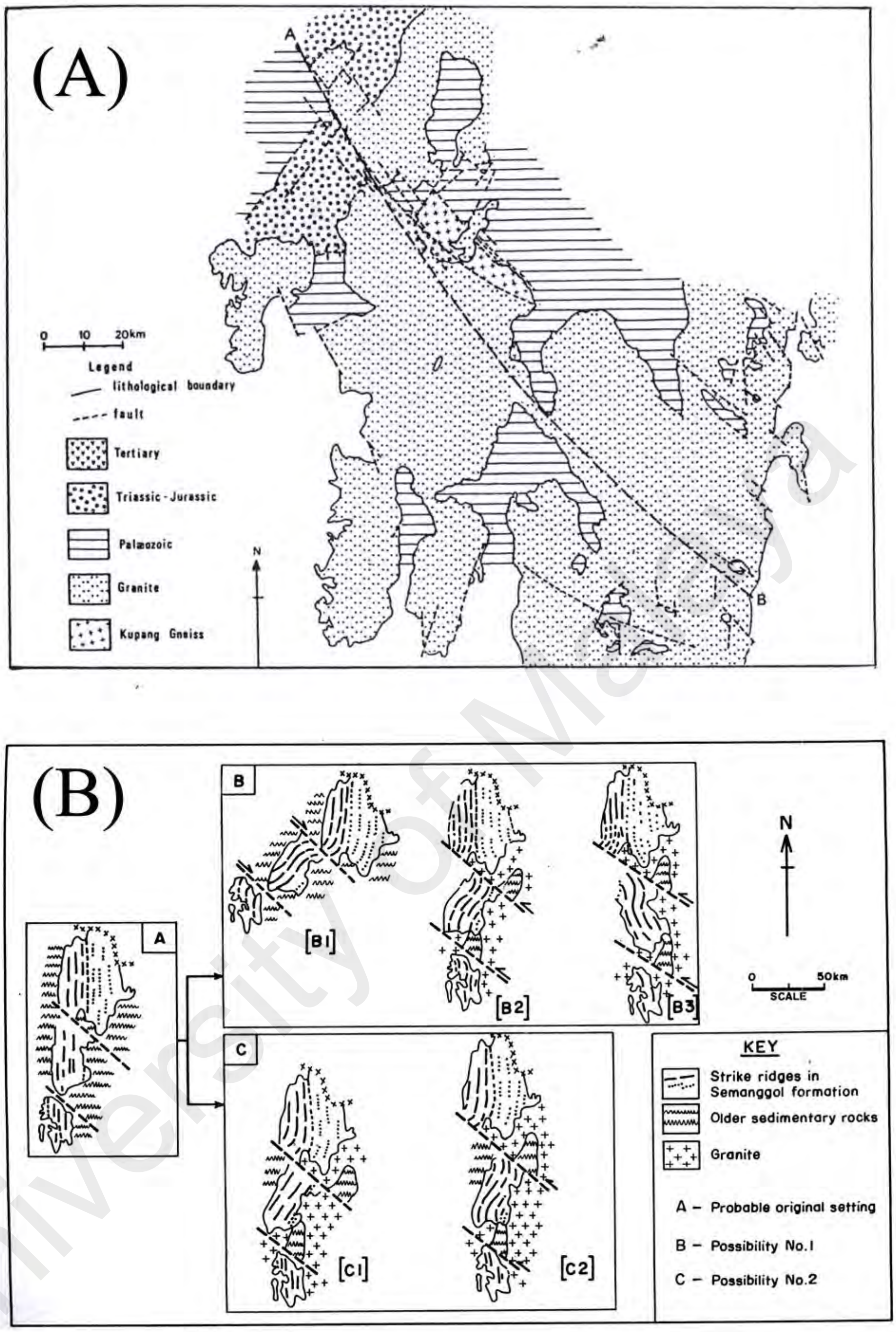

Figure 5.15: Interpretation of rock unit prior to movement along Bok Bak Fault: (A) Rock unit in Central Perak prior to 20 km sinistral displacement along Bok Bak Fault (Raj, 1982); (B) The two possible mechanism involving Bok Bak Fault in the modification of structural trend in Semanggol Formation in Kedah and Perak (Ibrahim et al., 1989).

Ibrahim et al. (1989) suggested the possibility of an earlier right lateral movement along the Bok Bak Fault (Figure 5.15), but this mechanism was not favoured due to absence of field evidences. With the finding of dextral shearing of mylonite along the Bok Bak Fault from this study, it is possible that dextral ductile shearing have indeed affected the surrounding rock as was suggested by the model. However, overprinting of brittle faults along ductile shear zone have made it difficult to estimate an accurate amount of displacement during ductile shearing, as there are no clear marker to indicate displacement during the period of deformation. As such, the various displacement values are representative of movement during the brittle deformation episodes. From the various figures on the displacement of the fault, a 20 to 30 km sinistral displacement occur along the NW fault set, and were later displaced dextrally NE fault set at a slip of less than 10 of kilometers.

5.6 Structural model

Burton (1965) used the fault model by Anderson (1951) to designate Bok Bak Fault as a wrench fault. A north-south confining force followed by an east-west compression, which result in opposing sense to original movement along the fault, was proposed for the kinematic of the Bok Bak Fault (Burton, 1965; 1988). It was however found that the model was insufficient in describing the observed sense of movement of the faults. Raj (1982) would later use the tectonic model of wrench fault of Moody and Hill (1956) to explain the trend of faults in east Kedah and Central Perak, where the NW and NE sets represent first order, left lateral strike slip faults, and second order, right lateral strike slip faults, respectively. This model is comparable with the Riedel Shear model used to interpret the lineaments in Chapter 3. A correlation between the model and the lineaments was illustrated in Figure 3.13; here, the model is compared with mapped brittle faults (Table 5.2 and Figure 5.16).

Table 5.2: Interpretation of simple shear model for Bok Bak Fault Zone, based on lineament plot in Chapter 3. Corresponding shears zone and faults from field mapping are noted in brackets.

Riedel Shear	Orientation	Brittle faults
Principal shear / Y shear	320°	NW sinistral Bok Bak Fault (D1 faults), NW shear zone (ductile deformation)
R-shear	305°	WNW sinistral faults (D1 faults)
P-shear	335°	NNW to NW sinistral faults (D1 faults)
R'-shear	065°	NE-SW dextral faults (D2 faults)
Shortening axis	095°	E-W fractures (D3 faults)

Field mapping and structural analysis of the faults shows that the Bok Bak Fault has undergone several brittle episodes, with the earliest one being the reactivation of the ductile shear zone to form brittle fault zone. The main NW set faults were reactivated from earlier ductile shear zone, with evidence of a ductile to brittle transition shear zone. Ductile deformation formed dextral movement in mylonite, which then undergone a change to sinistral strike slip movement, represented by brittle-ductile shear zone. Subsequent brittle deformations overprint these earlier ductile deformation structures.

The presence of ductile mylonite granite adjacent to sedimentary rock unit suggests the ductile part of the Bok Bak Fault zone has been exhumed to its present level. Reverse movement associated with strike-slip movement of D1 and D2 faults is most likely responsible to bring the deformed granite to a shallower depth. Strike slip D2 faults later cuts the earlier fault sets, and the effect is seen in remote sensing where the main NW faults were displaced by NE faults. Slickensides from D3 faults suggest a

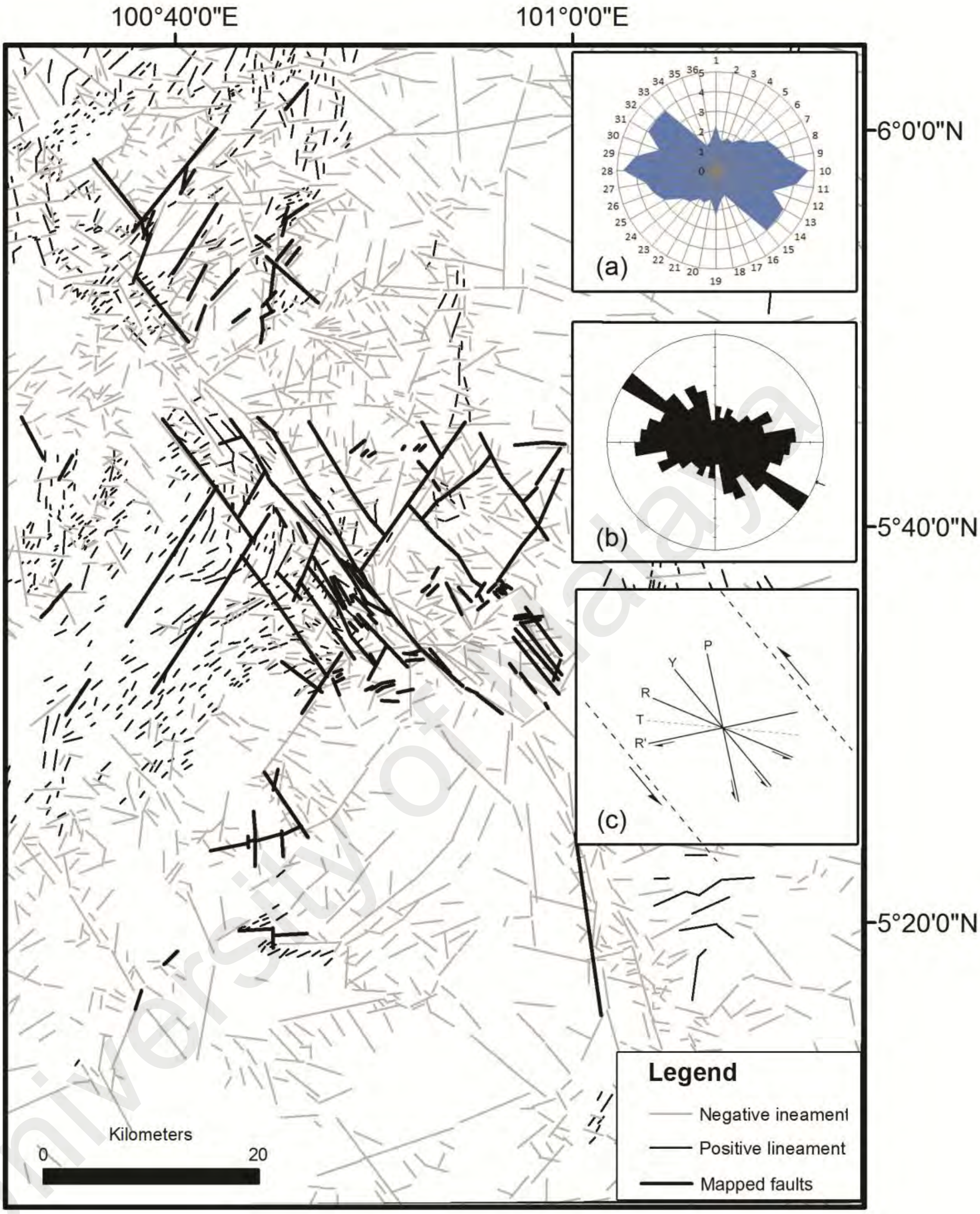

Figure 5.16: Riedel Shear interpretation of lineaments and faults. (a) Rose diagram of lineament; Rose diagram of mapped faults; and (c) Riedel Shear component

later extensional period of the Bok Bak Fault zone, which would form the E-W normal faults, as well as the overprinting of normal movement slickenside on earlier faults. The slip direction for all of the faults in the study area have highly variable slip direction, represented by more than one set of striae on the fault planes, and these were interpreted as representing of subsequent reactivations of the Bok Bak Fault.

5.7 Summary of brittle faulting

Three phases of brittle deformation (D1, D2, D3) were identified in the Bok Bak Fault Zone based on the trend and crosscutting relationship of faults found in the field. Brittle-ductile shear zone was found in Bukit Perak area, where it shares similar trend and sense of shear to D1 faults. The earliest of the brittle deformation, D1, is represented by sinistral oblique NW-SE to NNW-SSE faults, where the faults are steeply dipping with slickenside plunge of up to 60° to NE or SW. The second deformation phase, D2, forms dextral oblique reverse NE faults with steep dipping and slickenside plunge of up to 60° to NE or SW. The third deformation phase, D3, forms E-W normal faults with steep dip and high angle of plunge for the slickenside. Kinematic analysis of the slickensides point towards a change of stress system between the deformation phases, where E-W compressional stress of D1 faults was followed with NNW-SSE compressional stress of D2 and D3 faults. Movement of D1 and D2 faults are observable in remote sensing images, and these have been reported by several other workers. Trend of the faults from the different brittle deformation phase is comparable to the trend of structures formed using the Riedel Shear model, where the faults were compared with lineament plotting from remote sensing images. The occurrence of these different brittle deformation phases indicate that the Bok Bak Fault had undergone reactivation, where earlier brittle-ductile shearing was overprinted by subsequent brittle faults.

CHAPTER 6: TIMING FOR EVENTS OF BOK BAK FAULT

6.1 Introduction

Chapter 4 through 5 describes the different phase of deformation experience by the Bok Bak Fault, where earlier ductile deformation episode was overprinted by later brittle deformation phases. It is shown that the brittle deformations have produced the various fault sets that are observed as major lineaments in remote sensing, and structures in the field. This chapter discusses the studies that attempt to date several of the events along the fault zone, and attempt to correlate the ductile and brittle deformation phases of the Bok Bak Fault with these events.

Previous studies of Peninsular Malaysia relies on the studies of the age of the region's granite, using isotopic methods and thermochronological dating. Several studies have attempted to date the age of fault using isotopic dating, but there has yet been a comprehensive study on the dating of faulting events. Geochronologic and stratigraphic age dating is commonly relied on to constraint the age of faulting and other tectonic events. In this study, new result on radiometric dating along the fault zone was achieved, and the result compared with previous works on the timing of tectonic events, making it possible to narrow down the timing of faulting events of the Bok Bak Fault.

6.2 Magmatism age

Previous studies on the radiometric dating of granitic rocks in Malay Peninsula typically relies on traditional isotopic method such as Rb-Sr and K-Ar dating (e.g. Snelling, 1965; Bignell and Snelling, 1977; Krähenbuhl, 1991). Alongside these dating methods, several recent studies have utilized U-Pb zircon age dating to the granitic bodies in Peninsular Malaysia (e.g. Liew and Page, 1985; Searle et al., 2012), where Late Triassic igneous age was reported for the Main Range granite (Figure 6.1).

Ages from the Rb-Sr and U-Pb dating of the Main Range Granite of Peninsula generally show older ages than those achieved through K-Ar dating of the same rock unit. Ages achieved from K-Ar dating range from Late Jurassic to Eocene: these younger ages were attributed to argon loss in the granite as result of Late Triassic intrusions and young fault related disturbance, with area cut by WNW to ESE wrench faults showing clear argon loss in the granite (Bignell & Snelling, 1977). These younger K-Ar ages therefore does not necessarily represent the igneous age of the granitic rocks.

The timing of the initiation of the Bok Bak Fault, and its relationship to the granite emplacement has not been fully resolved, as there have been no previous radiometric dating on the fault rock along the fault zones. Several works discussed on the role of the Bok Bak fault in the formation of strike ridges and Tertiary basins (e.g. Raj et al., 1998; Zaiton, 2002), but the relation of the fault evolution with the granitic body is not well discussed. Burton (1972) noted that the main NW Bok Bak fault form the boundary of Kupang-Inas Granite, where a part of the Bok Bak fault is intruded by small body of Damar Granite on the northeastern part of the Kupang Granite,. From this, he suggested that fault initiation must have taken place prior to the intrusion of Damar Granite.

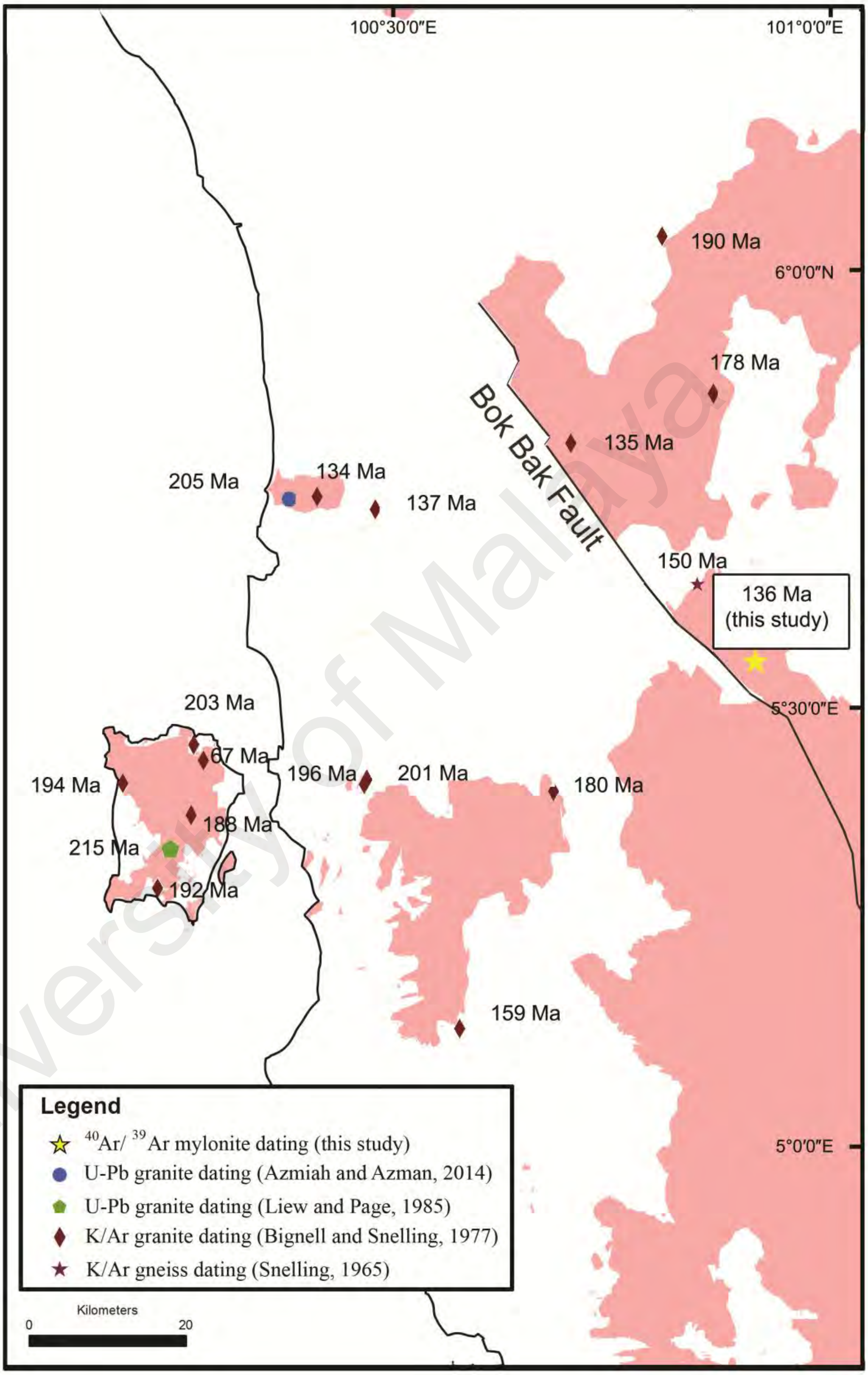

Figure 6.1: Ages of various dated granite in NW Peninsular Malaysia. Granite distribution modified from Mineral and Geoscience Department, 2014.

Mustaffa (2009a) suggested that the Bok Bak Fault was initiated in Upper Triassic from cross-cutting relationship between the fault and granite.

6.3 $^{40}Ar/^{39}Ar$ thermochronology

There have been little radiometric studies of fault rocks in Peninsular Malaysia, with the work by Zaiton (2002) providing radiometric ages as reference in reconstructing the tectonic evolution of the main faults of the Peninsula. Combined with a lack of studies on fault rocks, the age of ductile shearing of major faults of Peninsula is still poorly constrained. From new radiometric dating of the fault rock in this study, it is possible to place a constraint on the event of ductile deformation of these faults, by combining the isotopic dating of granitic rocks, along with several radiometric dating ages of other fault rocks.

For this study, a mylonite sample was sent for a $^{40}Ar/^{39}Ar$ thermochronology at the Activation Laboratories Ltd., Canada. The sample was collected from mapped shear zone in Baling-Gerik area (Figure 6.2), in which the geology have been discussed in Chapter 4. The biotite of the sample, specifically the recystallized biotite neocryst produced as a result of deformation, was separated from the rock for purpose of the analysis.

The result of the analysis of biotite is as follow:

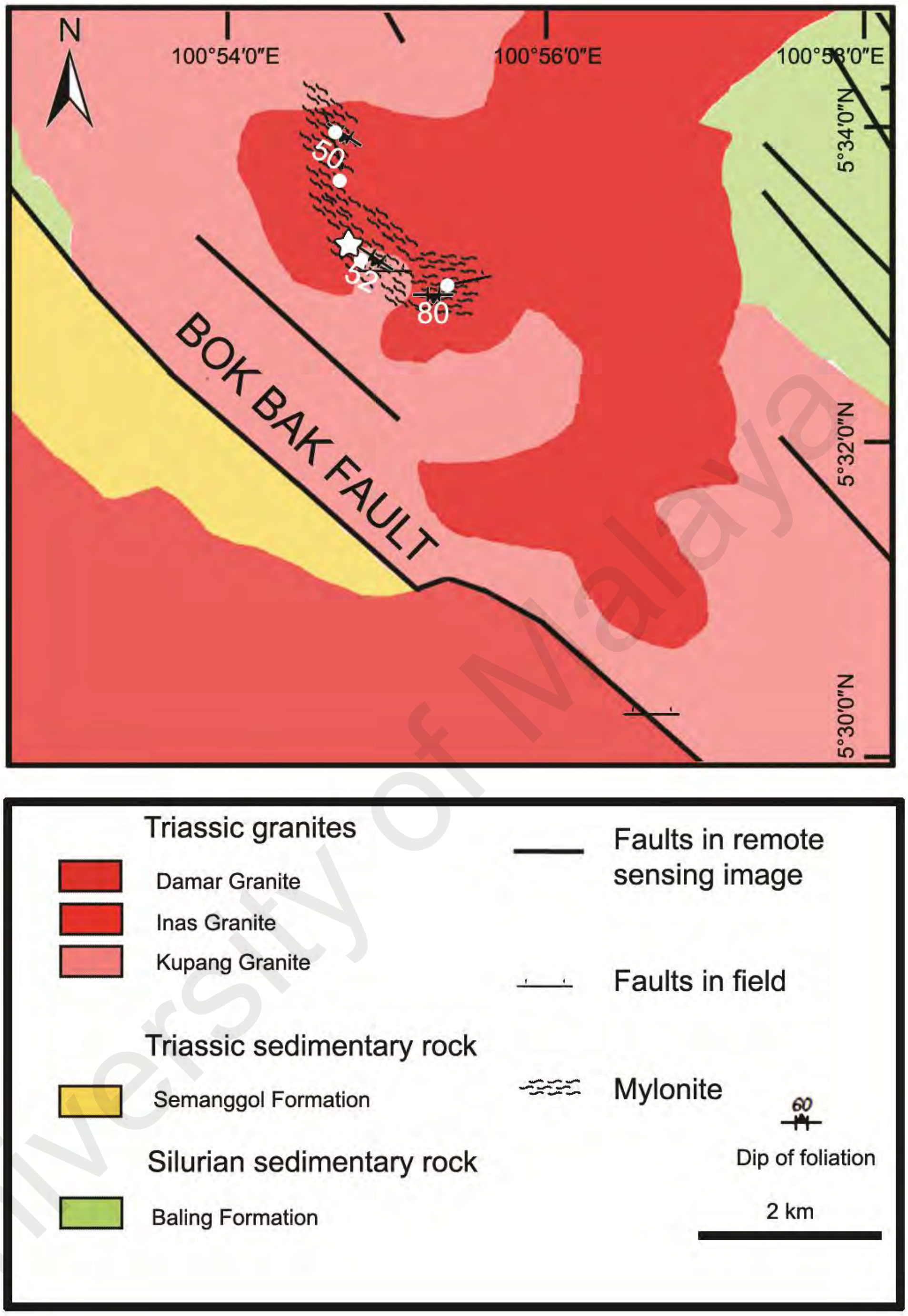

Figure 6.2: Mapped area of Baling-Gerik, showing mapped shear zone, sampling sites for microstructural study (circle), and $^{40}Ar/^{39}Ar$ dating sampling site (star)

6.3.1 Age of mica

The biotite is from mylonite exposed along the shear zone. In thin section, biotite appears to be mostly formed as secondary mineral in the mylonite, although some might be fragments of magmatic origins.

The result of the method is shown in Figure 6.3 and Table 6.1. The sample shows stair-stepped age spectrum, with increasing ages from 59.0 ± 1.1 Ma to 138.5 ± 2.0 Ma. The weighted mean plateau age (WMPA) is 136.1 ± 1.4 Ma. The Total Fusion Age (TFA) show significant difference in age with the plateau age (around 12 million years), and the Inverse Isochrone Age (IIA) plot points does not form significant linear trend.

The description of the dated sample and the factual presentation of the results and age spectra are given in Appendix A.

6.3.2 Discussion and interpretation of mica age

The $^{40}Ar/^{39}Ar$ date achieved in this study is the first radiometric dating for fault rock along the Bok Bak Fault. The age is close to a date achieved through K-Ar dating of biotite in granitic rock near the Bok Bak Fault trace (135 Ma) by Bignell and Snelling (1977). Several other similar age ranges are observed in K-Ar dating age of muscovite (134 Ma and 137 Ma) (Figure 6.1), although these are from locations are further from the main Bok Bak Fault. It was reported that in the K-Ar dating of granites of Peninsular Malaysia, the histogram of the data show maxima around 135 Ma and 85 Ma (Figure 6.4). The maxima of dates around Upper Jurassic – Lower Cretaceous was attributed by Bignell and Snelling (1977) to period of uplift, following the interpretation by Hutchison (1973a).

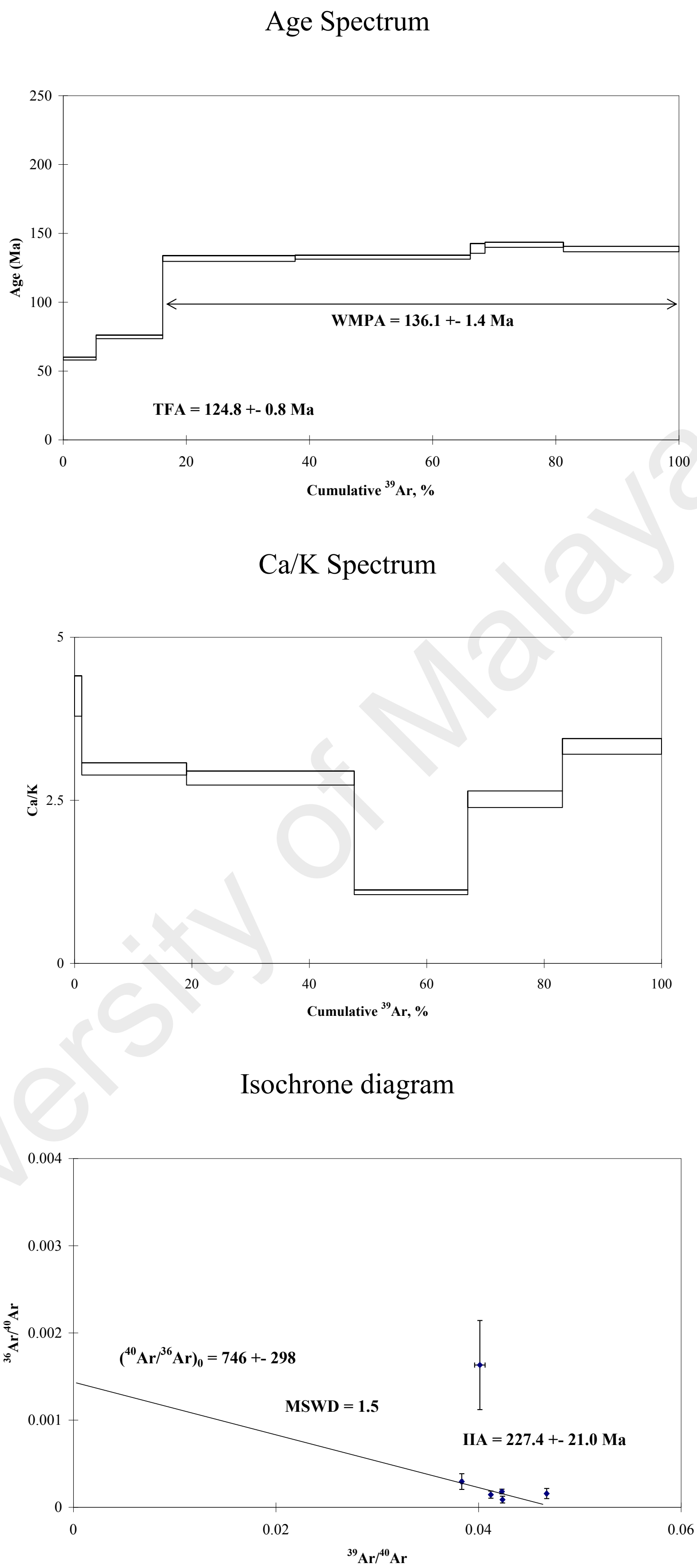

Figure 6.3: $^{40}Ar/^{39}Ar$ age spectrum and corresponding isochrone and Ca/K ratio for biotite from Baling-Gerik shear zone

Table 6.1: Tabulated data for $^{40}Ar/^{39}Ar$ dating of biotite

T^0C	$^{40}Arcc(STP)$	$^{40}Ar/^{39}Ar$	±1σ	$^{38}Ar/^{39}Ar$	±1σ	$^{37}Ar/^{39}Ar$	±1σ	$^{36}Ar/^{39}Ar$	±1σ	Ca/K	? ^{39}Ar (%)	Age (Ma) ±1σ	±1σ
500	$12.4*e^{-9}$	5.9368	0.0058	0.020502	0.000606	0.4453	0.0038	0.00298	0.00031	1.603	5.4	59.0	1.1
600	$33.4*e^{-9}$	7.9456	0.0109	0.022784	0.000922	0.2043	0.0124	0.00511	0.00037	0.735	16.2	74.8	1.3
700	$100.0*e^{-9}$	11.9456	0.0117	0.020939	0.000106	0.0033	0.0061	0.00145	0.00064	0.012	37.7	131.7	2.1
800	$130.5*e^{-9}$	11.7842	0.0092	0.020582	0.000093	0.0143	0.0029	0.00061	0.00044	0.051	66.1	132.7	1.4
885	$11.5*e^{-9}$	12.3703	0.0150	0.022618	0.000576	0.0995	0.0293	0.00064	0.00109	0.358	68.5	139.0	3.5
1000	$62.9*e^{-9}$	12.6905	0.0071	0.020553	0.000206	0.0125	0.0061	0.00090	0.00055	0.045	81.2	141.7	1.8
1130	$89.8*e^{-9}$	12.2978	0.0083	0.020464	0.000176	0.0096	0.0053	0.00054	0.00060	0.034	100.0	138.5	2.0

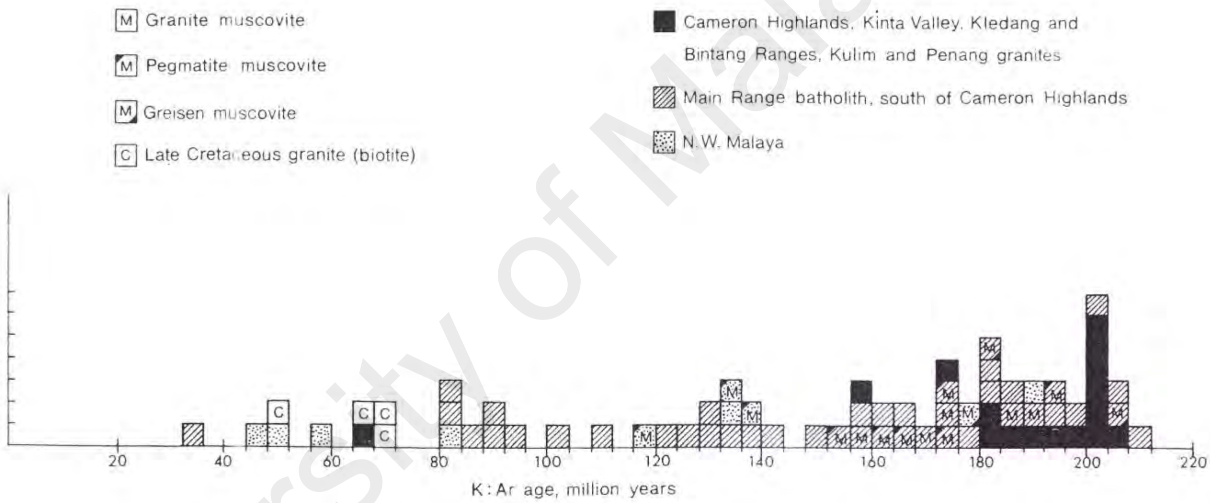

Figure 6.4: Histogram of K/Ar apparent ages of granite from Western Belt of Peninsular Malaysia (Bignell and Snelling, 1977)

An important consideration when using the 40Ar/39Ar method to date mylonitic rocks is whether the result should be interpreted as cooling ages, or the age of crystallization during deformation. Cooling ages require the dated mineral to form at a temperature greater than an assumed closure temperature (Tc). The Tc concept considers volume diffusion, for which temperature is the main control, to control isotope mobility (Dodson, 1973). Recrystallization due to the deformation lower than Tc would record timing of mineral growth, rather than cooling through Tc – and dated mineral would indicate the end of a deformation event (Dunlap, 1997). The deformation temperature of the dated mylonite (300 °C to 400 °C, section 4.5.2) is close to the Tc of biotite (300±50°C: Harrison et al., 1985): it is likely that the Ar system in the biotite could have been reset, and the obtained age would represent cooling age associated with deformation event. The variable age spectra of the mylonite sample (Figure 6.3) are indicative of partial resetting.

Snelling (1965) reported an age of 150 Ma for K-Ar dating of biotite of a rock unit referred as Kupang Gneiss. The rock was described as consisting of well-foliated micaschist with parallel bands of augen gneiss, and the mineralogy of this rock is entirely metamorphic with no relict igneous textures (Hutchison, 1973a). Due to the presence of clinopyroxene and microcline, and the absence of muscovite, the rock unit of Kupang Gneiss was interpreted to be formed under amphibolite facies, where it was subsequently upfaulted to its present condition. The age was interpreted to be related to faulting event, rather than the age of metamorphism, as the rock unit is bounded by fault (Hutchison, 1973a).

The Kupang Gneiss rock unit has been mapped in subsequent works as a part of the Bintang Hill Granite, and no further mentioning of the rock unit had appeared in recent publications. Field mapping in this study over areas previously mapped as Kupang

Gneiss show granite which are transected by shear zones. It is very likely that the rock dated by Snelling (1965) was a mylonite, where the foliation observed was in fact mylonitic texture. If so, the K-Ar age of the biotite would refer to the age of faulting, as suggested by Hutchison (1973a).

By compiling the radiometric dating ages of granitic rocks, the Early Cretaceous age is considered as representing the lower age constraint of the ductile shear of the Bok Bak Fault, while the Late Jurassic age represent an upper age constraint of the ductile shear. The constraint would bound the timing of ductile shear between 150 ± 8 Ma and 136.1 ± 1.4 Ma. In the absence of other thermochronology method of mineral along the fault zone, this is the best estimate on the timing for ductile deformation of the Bok Bak Fault.

6.4 Timing of brittle deformation

The timing of the brittle faulting deformation episodes for fault is more problematic, as there is no reliable mineral indicator to date directly, with no new mineral phase crystallized during the brittle deformations. Further complicating an accurate timing of the episodes is how there is little geological units that that were formed during the brittle deformation episodes of Bok Bak Fault, which could otherwise be used to constraint the brittle event timing.

The Jurassic-Cretaceous basins of Peninsular Malaysia were often related to the initiation of major fault zones. Some of these basins were dated from palynomorph studies, but in general they do not contain reliable index fossils to accurately date their timing of deposition. They were thought to be formed in strike-slip pull apart basins due

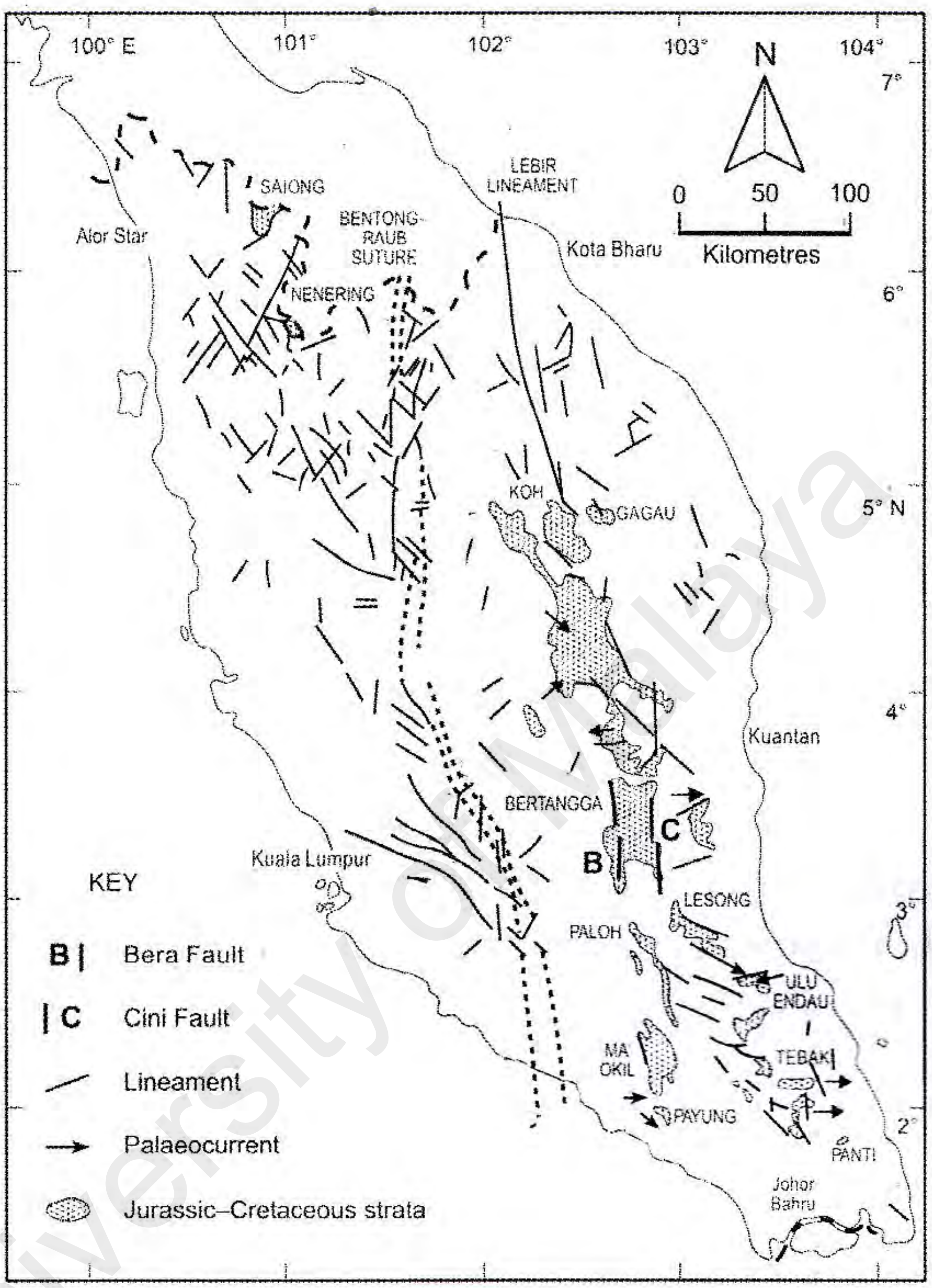

Figure 6.5: Jurassic-Cretaceous sediments of Peninsular Malaysia. Note the relationship between lineaments and sediment distribution (Nuraiteng, 2009)

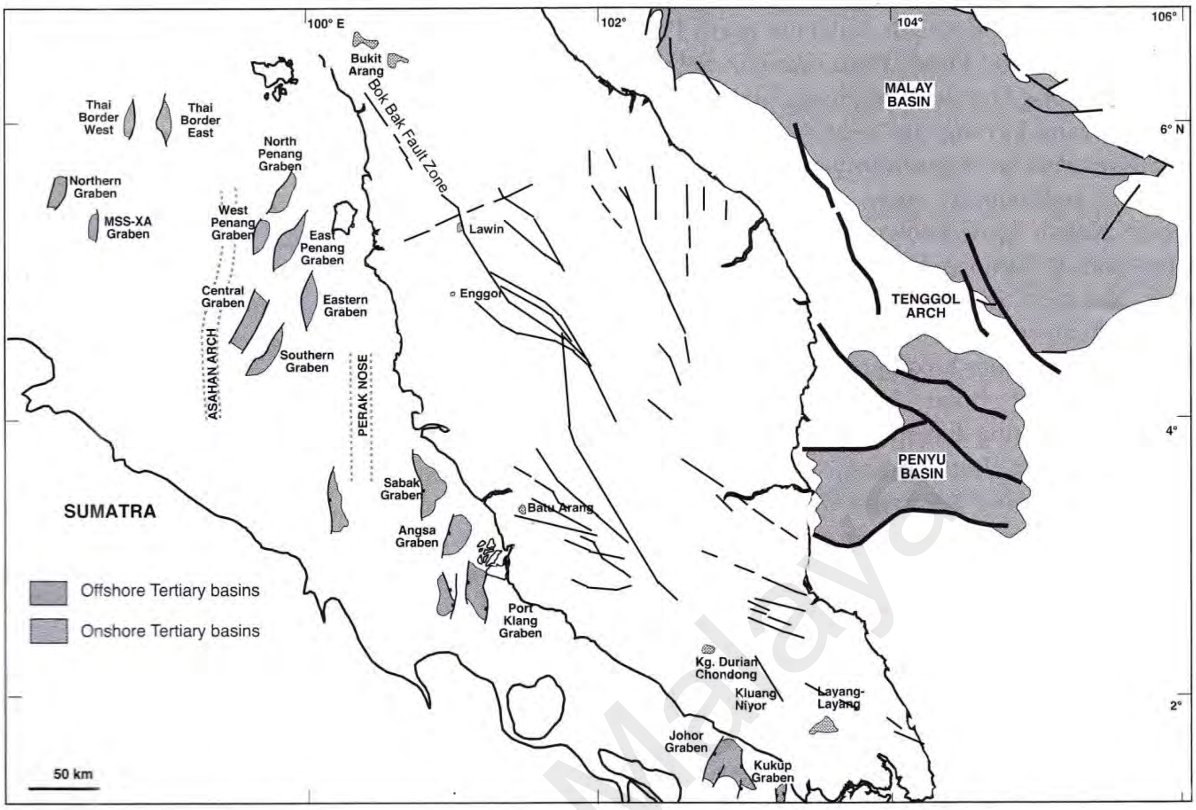

Figure 6.6: Tertiary basins of Peninsular Malaysia. Major faults plotted from Mustaffa (2009a). Geology from Raj et al. (2009).

to dextral movement along the Bentong-Raub Suture and Lebir Fault Zone during Upper Triassic (Tjia, 1996; Mustaffa, 2000), although Mustaffa (2009a) noted that these basins formed as pull-apart basin along dextral NNW-SSE to N-S faults, during or after the late stage of Main Range Granite emplacement (Late Triassic to Jurassic).

In the study area, rock units that are part of the Jurassic-Cretaceous basins are not found. There is however the report of the occurrence of continental redbed in NE Kedah, referred to as the Saiong Beds (Figure 6.5). Although this rock unit have not yield any fossils which can be dated, it was correlated with the Jurassic-Cretaceous Tembeling Group (Ong, 1969). It is unclear whether the rock unit is related to deformation along the Bok Bak Fault zone, but it seems likely that faulting plays a role in the formation of the rock unit, given the occurrence of the rock unit along intersection of major faults. Structures of the Jurassic-Cretaceous strata suggest they were deposited in a basin undergoing extension (Mustaffa, 2009b).

Further south from the study area, a small body of sedimentary rock referred to as the Lawin Basin occurs along the Bok Bak Fault trace. This sediment, along with other similar sediment bodies throughout the Peninsular, belongs to sets of Tertiary aged basins that were found to be developed along major strike slip faults (Figure 6.6). The basins were reviewed by Raj et al. (1998), where they were interpreted to develop in pull-apart basins that form as a result of sinistral displacement in Late Eocene to Early Oligocene along pre-existing NW-SE faults. The timing was based on correlation with regional tectonics of Sumatra, where the development of Tertiary grabens and half grabens were pinpointed to these time period.

Studies on offshore basins of Peninsular Malaysia have further developed the tectonic evolution of the fault system. The offshore basins of Malay Basin and Penyu Basin were thought to be developed by sinistral transtensional along pre-existing NW-trending shear zones during Late Eocene to Early Oligocene (Khalid et al., 1996; Mazlan, 1997). Reversal of shear during middle Miocene caused transpressive deformation, and inversion of these basins (Mazlan, 1997). A similar structural evolution is envisioned for the inland faults of the Peninsula (Zaiton, 2002; Zaiton et al., 2009). The period of subsidence of offshore basins coincide with a rapid exhumation observed from thermochronological study of granite (Cottam et al., 2013).

6.5 Neotectonic structures

Neotectonic refers to field of study that is a branch of tectonics, concerned with earth movement that both occurred in the past and are continuing at present day (Stewart and Hancock, 1994). The study is usually concerned with faults, recognizing if they are still active in present time. The dating methods used in neotectonic studies (Table 6.2) is out of the scope of discussion of this study, but two of these methods have been used by other workers in identifying recent activities along the Bok Bak Fault:

Mustaffa (2011), mapping deformed Quaternary sediments along Bok Bak Fault, have carried out radiocarbon dating of organic matters in the sediments, which gives the age between 2000 to 400 years ago. The age is interpreted as the age of seismic activities, and placed a constraint on the age of neotectonic activity along the fault zone. Apparent displacement and liquefaction structures in the sediment are seen to indicate seismicity as a result of reactivation of the fault in recent time.

There have been several reports of recent seismicity in the vicinity of the Bok Bak Fault in recent time. Burton (1965) in his study of the Bok Bak Fault had noted the report of tremor in Baling area about 40 years earlier, which he categorized at approximately Scale V on the Modified Mercalli scale. In 20 August 2013, an earthquake of 4.1 magnitude on the Richter scale hit Kupang, with the epicenter located at Tasik Temenggor, Perak, latitude 5.4° N and longitude 101.4° E (Jabatan Meteorologi Malaysia, 2013). There was no subsequent tremor, nor any report of structural damage or ground rupture. When plotted, the epicenter of the 2013 tremor is located on the intersection of NW-SE and NE-SW trending lineaments (Figure 6.7). While the epicenter is located further from the main Bok Bak Fault trace, it does show that area close to the fault is susceptible to seismic activities.

Table 6.2: Summary of dating methods commonly used in neotectonic studies (Stewart & Hancock, 1994)

	Dating method	Material dated
Annual	Historical records	Eye witness accounts, historical documents, legends
	Dendrochronology	Annual tree rings
	Varve chronology	Deformed lake sediments
Radiometric	Carbon-14	Charcoal, peat and shells from offset datum horizon
	Uranium-series	Fossil coral reefs, molluscs, bone, pedogenic carbonate
	Potassium – argon fission track	K-bearing igneous rocks, volcanic glass shards, zircon
Radiologic	Uranium trend	Alluvium colluvium, loess
	Thermoluminescence	Quartz and felspar grains in fault scarp-derived colluvium
	Electron spin resonance	Quartz-bearing fault gouge
Process-oriented	Amino-acid racemization	Molluscs, skeletal material
	Lichenometry	Lichen on glacial moraines and fault scarps
	Soil chronology	Degree of soil development on offset geomorphic surfaces
	Rock weathering	Rock varnish, weathering rinds
	Slope morphometry	Fault scarps and offset erosional scarps
Correlative	Stratigraphy	Scarp-derived colluvial wedges
	Archaeology	Pot sherds and other artifacts
	Palynology	Offset glacial moraines
	Palaeomagnetism	Fault gouge

It is unclear whether the fault is currently active, but given the evidence of Quaternary sediment deformation and reports of seismicity in the vicinity of the fault zone, the Bok Bak Fault is a potential zone of weakness that is susceptible to reactivation by present day stress system, and perhaps similar to the Bukit Tinggi Fault, represent recent reactivation of older faults due to the deformation of Sundaland core (Mustaffa, 2009c).

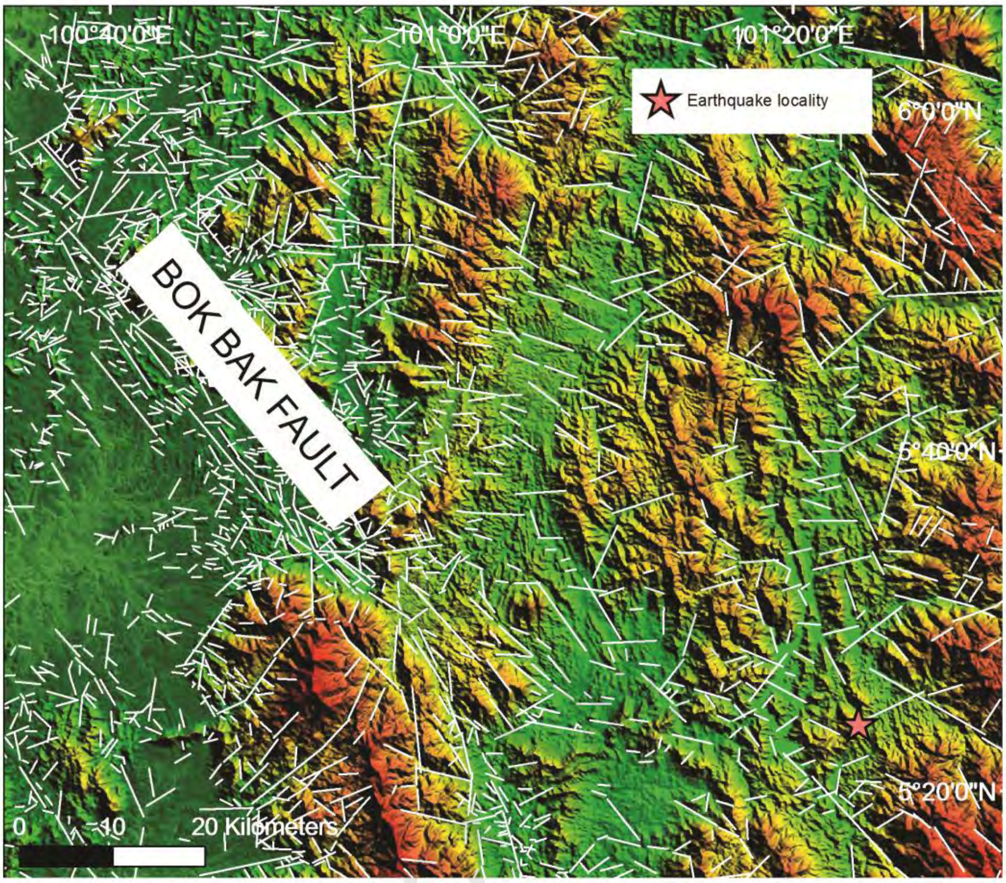

Figure 6.7: SRTM shaded relief map showing lineaments and the 2013 earthquake epicenter

CHAPTER 7: DISCUSSION AND CONCLUSION

The study aimed to provide a better understanding of the kinematic history of the Bok Bak Fault, and its correlation with regional tectonic history of the region. Findings from this study is discussed in the context of the tectonic history of Peninsular Malaysia and the region:

7.1 Correlation with Peninsular Malaysia tectonic history

Based on the timing deduced for the ductile and brittle deformation of the study area in previous chapter, a correlation between the Bok Bak Fault deformation events in the study area with major tectonic events of the Peninsular Malaysia is thus presented:

1) Initiation of N-S and NNW-SSE faults

NNW-SSE faults such as the Bok Bak Fault was believed to be initiated as dextral strike-slip faults after the amalgation of two tectonic blocks of Peninsula (Chapter 2) (Mustaffa, 2000), where movement along these faults took place during or at the late stage of the emplacement of Main Range Granite, during Late Triassic to Jurassic (Mustaffa, 2009a). Radiometric dating from previous studies (Chapter 6) placed the constraint of ductile deformation (Chapter 4) of the Bok Bak Fault as Late Jurassic to Early Cretaceous. This age is interpreted as representation of the early stage of the fault, where the fault was initiated as a ductile shear zone.

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Table 7.1: Summary of tectonic events in Peninsular Malaysia which affected the Bok Bak Fault

Age	Events
Early Cretaceous	Dextral reverse NNW-SSE faults during or after late stage of Main Range Granite emplacement (Late Triassic – Jurassic) followed with dextral transtention on overlapping of N-S faults and NNW-SSE faults (Tjia, 1996; Mustaffa, 2000) Dextral to thrust movement of Bok Bak Fault during ductile deformation in Early Cretaeceous (this study)
Late Cretaceous	Regional exhumation (Krähenbuhl, 1991; Cottam et al., 2013) Sinistral movement of NNW-SSE, NW-SE, and WNW-ESE faults (Zaiton, 2002)
Late Eocene to Early Oligocene	Offshore and inland basins developed by sinistral transtensional along NW-trending shear zones (Khalid et al., 1996; Mazlan, 1997; Raj et al., 1998)
Miocene	Reversal of shear of offshore basins; transpressive deformation and inversion (Mazlan, 1997)
Quaternary	Holocene seismicity (Mustaffa, 2011); Earthquake report in Baling during 1920s (Burton, 1965); Perak 2013 earthquake (Jabatan Meteorologi Malaysia)

2) Late Cretaceous reactivation

An exhumation event in the Peninsula during Late Cretaceous to early Cenozoic were found from $^{40}Ar/^{39}Ar$ and ZHe analysis of granite (Krähenbuhl, 1991; Cottam et al., 2013). The period represents sinistral reactivation of NNW-SSE, NW-SE, and WNW-ESE faults of the Peninsula (Zaiton, 2002). NNE-SSW strike-slip faults were formed during the same time (Mustaffa, 2000), at the same time as intrusion of Kemahang Granite, Stong Complex, and deformation of continental deposits (Mustaffa, 2009a). Brittle faults (Chapter 5) is most likely developed during this period, two main brittle episodes which result in the D1 faults and D2 faults.

3) Tertiary brittle reactivation

Thermochronological analysis of granitic rocks of the Malay Peninsula show several periods of exhumation, during Late Cretaceous to early Paleogene, and Eocene (Krähenbuhl, 1991; Cottam et al., 2013). The Late Eocene to Oligocene rapid exhumation coincide with significant subsidence in offshore areas (Cottam et al., 2013), during time where sinistral movement along pre-existing NW-SE fault zones formed the Tertiary offshore and onshore basins (Raj et al., 1998; Khalid et al., 1996; Mazlan, 1997). Reversal of the sense of shear of these fault zones took place during Middle Miocene (Mazlan, 1997). N-S, NNW-SSE, and WNW-ESE faults were reactivated as dextral strike slip during this period (Mustaffa, 2009b).

The Tertiary reactivation of earlier faults were associated with the Indian Plate collision with Eurasia in early Cenozoic time (Zaiton, 2002; Mustaffa, 2009a). The normal faults of D3 faults (Chapter 5) is most likely formed during this extensional period, which would overprint earlier movement along D1 and D2 faults.

4) Quaternary deformation

Quaternary deformations have been reported along the Bok Bak Fault, from radiocarbon dating of deformed unconsolidated sediments along the fault zone (Mustaffa, 2011), and report of seismicity in the vicinity of the Bok Bak Fault (Burton, 1965; Jabatan Meteorologi Malaysia, 2013). These evidences point out that deformation along the Bok Bak Fault have carried on until recent time, and as with other major faults such as the Bukit Tinggi Fault, represent reactivation of older faults in recent time due to the Sundaland core being deformed (Mustaffa, 2009c).

7.2 Correlation with regional tectonic history

The Late Cretaceous to Paleogene period represent a crucial time for faulting and deformation in Sundaland, one which is observed Thailand, Burma, and Malaysia (Morley, 2004, 2012). The event is however not well understood in the context of Peninsular Malaysia due to lack of detailed studies.

Studies of other faults of the Malay Peninsula have reported an age of Late Cretaceous and Eocene for the mylonite (Zaiton, 2002). Thermochronological analysis of granitic rock of the Malay Peninsula have found record of exhumation during Late Cretaceous to early Paleogene, and Eocene (Krähenbuhl, 1991; Cottam et al., 2013). The older age from thermochronology analysis of mylonite in this study therefore appear to be related to a much earlier tectonic events than the Late Cretaceous to Early Paleogene tectonic events observed in Sundaland (Morley, 2012).

In Sumatra and Myanmar, subduction takes place during Jurassic to Early Cretaceous (Hutchison, 1973b, 1983, 2007; Hall et al., 2009; Hall, 2012; Morley, 2012), followed by island arc collision in Middle Cretaceous, which forms the Woyla Terrane and possibly the Mawgyi Nappe (Barber & Crow, 2009). The Jurassic to Early Cretaceous is a time which Sundaland became cratonized and major strike-slip and block fault developed (Gobbett & Tjia, 1973). The NW-SE and NE-SW faults of Peninsular Malaysia was assumed to be activated during the period of collision of the Burma Arc to the East Asian Continent during Cretaceous time (Krähenbuhl, 1991).

From this study it is shown that the Bok Bak Fault undergone an early ductile dextral strike-slip to thrust deformation that was initiated as early as Late Juarassic to Early Cretaceous. The ductile deformation of the Bok Bak Fault post-date the Indosinian Orogeny event which have been well dated by various literatures (refer to Metcalfe, 2013 for review) and the intrusion of Main Range Granite. Subsequent tectonic events such as exhumations during Late Cretaceous to Early Paleogene, and Eocene (Krähenbuhl, 1991; Cottam et al., 2013), and subsidence of offshore basins (Khalid et al., 1996), which have been observed in other area of Sundaland, appears to be responsible for reactivation along the Bok Bak Fault.

7.3 Conclusion

The aim of this study was to answer questions on the kinematic history of the Bok Bak Fault. Remote sensing study and field mapping have helped in delineating the extension of the fault zone, and effect of the fault to other rock units could be observed. The lineament trend could be fit under the Riedel Shear model, indicating their origin as occurring along a strike-slip fault zone.

Ductile episode of the fault zone resulted in mylonite along NW-SE shear zone, which indicate dextral to thrust movement. A temperature range of 300 °C to 400 °C was interpreted from the microstructure studies of the minerals. Radiometric dating of mica gave a constraint of Late Jurassic to Early Cretaceous as the age of ductile deformation. The ductile deformation show transition to brittle deformation, forming zone of brittle-ductile shear zone.

The earliest brittle episode, D1, forms NW-SE and NNW-SSE faults with sinistral and thrust movements. D2 episode forms NE-SW faults with dextral and thrust movement, which cuts D1 faults. The last brittle episode observed, D3, forms E-W normal faults, which result in the overprinting of normal movement along older strike slip and thrust movement of older faults. Kinematic study from fault planes indicate a strike slip deformation during D1 episode, and oblique slip deformation during D2 and D3 episodes.

The different phases of the kinematic history of the Bok Bak Fault is representative of several periods of reactivations of other major fault zones in Peninsula. The initiation of the Bok Bak Fault would precede the event of convergence between Indian and Asian plate, with the formation post-dating the Indosinian Orogeny event. Other major tectonic events such as exhumations and subsidence of offsore basins have all seem to play a role in reactivating the Bok Bak Fault, represented by the different brittle episodes observed.

7.4 Recommendation for further studies

There are a number of gaps in the knowledge and involvement in this research, and would benefit from further research:

1) The precise timing of the early ductile deformation still remain inconclusive, as the dated biotite from the mylonite could represent the cooling age of the fault, rather than the actual deformation age. Further thermochronology method (e.g. $^{40}Ar/^{39}Ar$, (U–Th–Sm)/He, and fission track data) and geochemistry studies along the fault are needed to further constraint the timing of deformation of the fault.

2) Most of the brittle age for the fault is derived from cross cutting relationship and correlation with regional events. Methods to date brittle deformation events could greatly give a more accurate timing of the brittle deformation of the Bok Bak Fault.

3) This study is mostly focused on the effect of ductile shearing and brittle deformation in granite. A more detailed study of the effect of the deformation on

sedimentary (or meta-sedimentary and metamorphic rock assemblage) is important to more accurately study the tectonic event of Peninsula during Late Mesozoic to Early Cenozoic – especially concerning the continental basins, of which is still not properly understood with regards to the major fault zones of Peninsula.

4) There has not been much intensive field studies for the extension of the Bok Bak Fault in Perak, and the brittle faults and sheared granite there could be studied in detail. The result could be compared with this study, to see if there is significant change in trend of structural elements and mineral texture (for mylonite) along the main trace of the Bok Bak Fault.

5) A comprehensive study on the similarity and difference between the timing and kinematic history of the Bok Bak Fault and other major faults of the Malay Peninsula such as the Bukit Tinggi Fault and Kuala Lumpur Fault would be beneficial to further refine the tectonic evolution of the Malay Peninsula.

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