# Analyse morphotectonique et géomorphologique de la bordure nord de Bornéo (Malaisie)

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# Geomorphology and Morphotectonic Analysis of north Borneo

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*“Savor the irony should those orogens most alluring to hard-rock geologists owe their metamorphic muscles to the drumbeat of tiny raindrops”*

*(Hoffman, P.F., Grotzinger, J.P., 1993. Orographic precipitation, erosional unloading, and tectonic style. Geology 21, 195–198.)*

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# Introduction

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## 1.1 Overview

A myriad of geomorphic expressions consisting of fascinating physical landscapes and intricately sculpted landforms envelop the upper lithosphere of our planet. The scientific analysis of Earths landscapes and the investigation of processes that mold landforms are the fundamental facets of geomorphology. Geomorphic examination of a region includes the genetic analysis of landform assemblages and their spatial distribution to decipher the origin and establish an understanding of its evolution. Geomorphology is a science of immense significance with regard to processes that carve topography in the past and those that alter them today. In essence, the relationship between land surface forms and processes is a close and intricate one. The landform elucidates boundary condition for processes acting on it.

However, in acting on the surface the processes themselves modify the underlying form – the canvas they act on – and thus, finally, the intensity and the patterns of themselves. Thus, topography is both the result of past geomorphic processes and the stage for present geomorphic processes which reshape it again for future geomorphic processes (Swanson et al., 1988; Dehn et al., 2001; Straumann, 2010).

### 1.1.1 The Evolving Landscape: Coupling of Tectonics and Geomorphic Processes

The Earth constitutes a succession of nested spheres of which the interface between the lithosphere, hydrosphere and atmosphere is by far the most complex and dynamic in nature. This interface houses landscapes that appear static to observations made over short periods of time but are extremely active entities undergoing rapid change in geological terms. The continental topography we witness today is by and large a product of processes and their repercussion of the immediate past. In principle, landscapes have the capability to register recent history of Earth's surface and its environments.

Landscapes are created, constantly modified and torn asunder through the action of processes driven by external forces arising from the surface of the earth and internal forces from within the planet (Sharp, 1982). These processes combined together cause physical stresses and chemical actions on surface material that change the configuration of the earth's surface are collectively known as geomorphic processes. The links between these driving forces and the resulting topography are complicated by delays between a forcing factor changing and the topographic expression of that change, leading to a system response time characteristic of the forcing factor and the properties of the system it is acting upon (Whipple and Tucker, 1999; Whipple, 2001; Saville, 2013).

The internal forces also called as endogenetic processes are responsible for continuously elevating relief and constructing parts of the Earth's surface. External forces known as exogenetic processes operate by wearing down relief created by endogenic processes. Variations in land surface forms and physical topography persist as long as the opposing actions of exogenic and endogenic forces remain active. Processes that shift and uplift or build up portions of the crust known as diastrophism or tectonism and volcanism are considered as endogenic processes. Whereas, geomorphic processes such as weathering, erosion and deposition express exogenic forces.

Tectonism comprises of two vital mechanisms – orogenic and epeirogenic processes. Orogenic processes are responsible for mountain building through crustal folding resulting in severe deformation affecting long and narrow belts of the earth's crust, while, epeirogenic processes involve uplift and warping of large regions on the surface of the earth. In order to measure amount of geomorphic deformation resulting from tectonic processes, it is necessary to have identifiable features that have been displaced called geomorphic markers (Burbank and Anderson, 2001). The best geomorphic markers are readily recognizable landforms, surfaces, or linear trends.

Exogenic processes derive their energy from the atmosphere and also the gradients created by tectonic factors. The effects of most exogenic geomorphic processes are minor and slow and may be imperceptible in a short time span, but will in the long run affect the rocks severely due to persistent activity. Climate and climatic elements such as temperature and precipitation are among the key driving forces behind exogenic geomorphic processes that strip down surface material by erosion, weathering and mass movement, ultimately, modifying landscapes (Burbank and Anderson, 2001). In order to denude, transport and deposit earth material, exogenic processes have to depend on elements of nature that are set mobile due to gravitational forces and earth surface gradients. These elements, called geomorphic agents, are capable of removing material and moving them over slopes and finally depositing them at lower levels. Running water, glaciers, ground water, waves and currents can be classified as geomorphic agents.

### 1.1.2 Fluvial Systems: The Arteries of Continents

Fluvial networks are dynamic systems susceptible to alterations resulting from successful recurrent disturbances in equilibrium over timescales ranging from seconds to tens of thousands of years. They evolve remarkably, adjusting diversely to the wide range of environments in which they can be observed. Topography inherited by constant interaction of fluvial systems and consequent erosion, envelop extensive reaches of the earth's surface. Based on controlling factors such as landscape morphology, lithology and surface gradient, fluvial systems can develop patterns pertaining to specific conditions within a drainage basin (Charlton, 2007).

Rivers flow into oceans, although some drain to lakes and inland seas, meanwhile some others dry up completely before reaching the ocean. Every river drains areas of continents

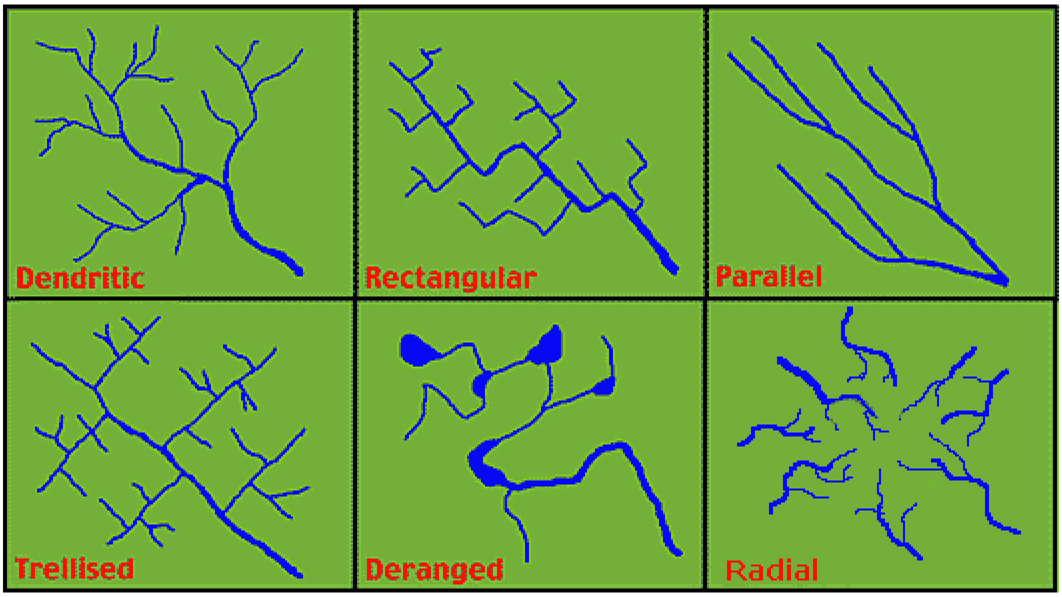


**Figure 1.1** Some of the most commonly encountered drainage patterns. Figure source: https://laulima.hawaii.edu.

called its drainage basin or catchment or watershed. The drainage area may be defined as the area which contributes water and sediments to a particular channel or sets of channels. It is the source area of the precipitation eventually provided to the stream channels by various paths. As such it forms a convenient unit for the consideration of the processes determining the formation of specific landscapes in the various regions of the earth. It provides a limited unit of the earth's surface within which basic climatic quantities can be measured and characteristic landforms described, and a system within which a balance can be struck in terms of inflow and outflow of moisture and energy.

Drainage patterns by theory specify shapes or designs the individual streams may form. A distinction can be made between the patterns of the individual tributaries and their spatial relationships to one another. They can be termed as drainage arrangements since they refer more to the spatial relationships of individual streams than to the over-all pattern made by the individual drainage lines. It is generally recognized that drainage patterns reflect the influence of such factors as initial slopes, inequalities in rock hardness, structural controls, recent diastrophism and the recent geologic and geomorphic history of the drainage basin. Because drainage patterns are influenced by so many factors they are extremely helpful in the interpretation of geomorphic features, and study of them represents one of the more practical approaches to an understanding of structural and lithological control of land form evolution. The most commonly encountered drainage patterns are dendritic, trellis, radial, parallel, rectangular and deranged (Figure 1.1). Of these, dendritic patterns are by far the most common. They are characterized by irregular branching of tributary streams in many directions and at almost any angle, although usually at considerably less than a right angle. They develop upon rocks of uniform resistance and imply a notable lack of structural control. Dendritic patterns are most likely to be found upon nearly horizontal sedimentary rocks or in areas of massive igneous rocks, but may be seen on folded or complexly metamorphosed rocks, particularly when imposed upon them by superposition. Trellis patterns display a system of sub-parallel streams, usually aligned along the strike of the rock formations or between parallel or nearly parallel topographic features recently deposited by wind or ice. The major streams frequently make nearly right-angled bends to cross or pass between aligned ridges, and the primary tributary streams are usually at right angles to the main stream and are themselves joined at right angles by secondary tributaries whose courses commonly parallel the master stream. Trellis patterns reflect marked structural control of most stream courses, except perhaps the trunk streams. The tributary valleys are usually subsequent strike valleys. A variety of the trellis pattern is the fault trellis pattern, which may be found where a series of parallel faults have brought together alternating bands of strong and weak rock. Radial patterns have streams diverging from a central elevated tract. They develop on domes, volcanic cones, and various other types of isolated conical or sub-conical hills. Parallel patterns are usually found where there are pronounced slopes or structural controls which lead to regular spacing of parallel or near-parallel streams.

Landscape results from the competition of tectonic and geomorphic processes (Burbank and Anderson, 2001). The impact of tectonics on landscape development and geomorphic processes in tectonically active regions can be quantitatively and qualitatively analyzed by studying the drainage system (Jackson et al., 1998; Sung and Chen, 2004; Delcaillau et al., 2006; Ramsey et al., 2008; Bahrami, 2013). The drainage system, ergo, is a key element of the physical topography and analyzing their evolution can provide information on denudational history and tectonic impacts on landscape development (Small, 1978; Vandana, 2013).

The deviation of course of present-day river networks from their common regional patterns, termed as drainage anomalies, are a product of active tectonic deformation (Zernitz, 1932; Howard, 1967; Clark, et al., 2004) and bedrock resistance. Hence, drainage patterns and their corresponding anomalies have potential to archive information regarding regional and local tectonic events (Deffontaines et al., 1992; Simoni et al., 2003; Delcaillau et al., 2006, Ramasamy et al., 2011; Bahrami, 2013). In tectonically active zones, tectonics may directly affect the development of fluvial systems through the modification of stream gradients, tilting of surfaces and/or structural deformation (Maher and Harvey, 2008).

The geometry of river networks is sensitive to surface uplift in actively deforming regions, thus recording the history of tectonically driven crustal motions (Howard, 1967; Seeber and Gornitz, 1983; Oberlander, 1985; Cox, 1994; Jackson and Leeder, 1994; Clark et al., 2004). Innate geomorphological characteristics of motions related to tectonics, reflect features such as linear valleys, ridgelines, steep slopes of uniform aspect and tilt of terrain (Jordan, 2003).

Ancient riverine networks termed as paleochannels or paleo-valleys are remnants of stream channels which are good geomorphological indicators of fault movements related to tectonics, redirecting the flow regime, abandoning ephemeral or perennial systems, that now stands buried or lost (Bates and Jackson, 1987). Rearrangement of the paleo-fluvial flow to present day configuration can be the contribution of recent tectonic deformation events which produces changes in polarity of regional slopes (Bonnet, 2009). As a result of these tectonic events, the vestiges of former floodplains may be exposed or/and uplifted. These former floodplain deposits are termed as fluvial terraces. Some terraces may have little or no alluvium on them and may thus be classed as bedrock terraces in contrast with alluvial terraces, which consist of gravel, sand and finer alluvium. Terrace staircases can be results of regional uplift (Burbank et al., 1996; Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002; Bridgland and Westaway, 2008; Cunha et al., 2008; Claessens et al., 2009; Viveen, 2012) whereas differential tectonic movements produce unpaired terraces along the stream (Peters and van Balen, 2007; D'Allesandro et al., 2008; Larue, 2008; Martins et al., 2009).

### 1.1.3 Application of digital terrain data and GIS in geomorphology

Geomorphic interpretations using drainage and their anomalies can be easily and rapidly facilitated by employing remotely sensed digital terrain data such as Digital Elevation Models (DEMs) (Jordan, 2003). Digital topographic data can be effectively integrated and organized within Geographic Information Systems (GIS) in order to extract variables for numerical and statistical analysis of geomorphic characteristics of drainage basins and stream networks (Figure 1.2). DEMs store information as point elevation data assigned to each pixel on either a regular grid or a triangular integrated network allowing the analysis of the three-

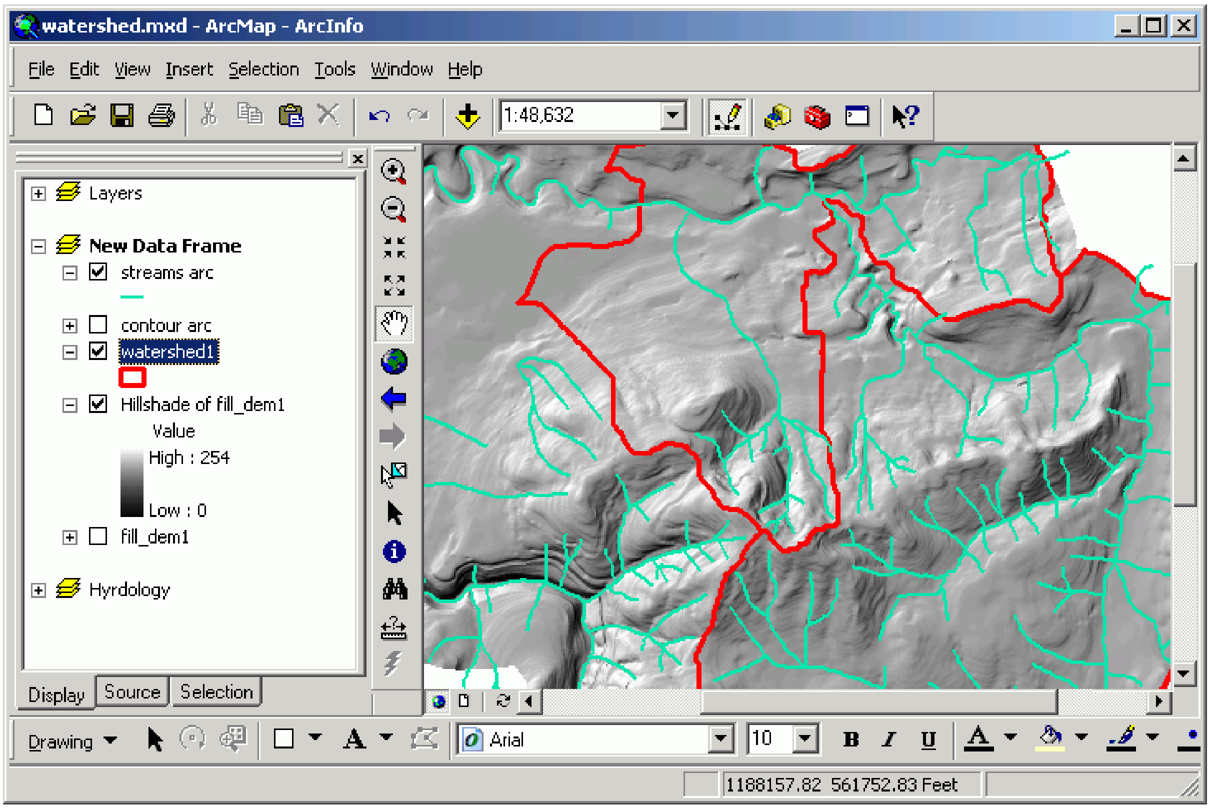


**Figure 1.2.** A stream network extracted from a Digital Elevation Model within a GIS environment. Figure source: https://courses.washington.edu/gis250/lessons/hydrology/

dimensional properties of landscape (Zhang and Montgomery, 1994). Data acquired through remote sensing techniques have been lucratively applied in various fields of study including but not limited to land cover/ land use, medical sciences, forensic investigation and socio-economics. Landscape characterization and interpretation of morphological features and their tectonic implications utilizing digital terrain analysis have been successfully applied by earth scientists worldwide (e.g., Tarboton et al., 1991; Dietrich et al., 1993; Montgomery and Foufoula-Georgiou, 1993; Willgoose, 1994; Moglen and Bras, 1995; Tucker, 1996; Bonnet et al., 2000; Snyder et al., 2000; Hou and Mauger, 2005; Ribolini and Spagnolo, 2008; de Fátima Rossetti et al., 2009; Nandini and Sanjeevi, 2011). The use of this form of digital data is a distinctly pragmatic approach for studying and virtually "visiting" landscapes encompassing large areas where direct physical access may be limited due to hostile terrain and/ or thick vegetation cover. Digital terrain analysis can be optimally applied especially in inaccessible regions of physiographic nature dominated by thick vegetation (e.g., de Fátima Rossetti et al., 2009).

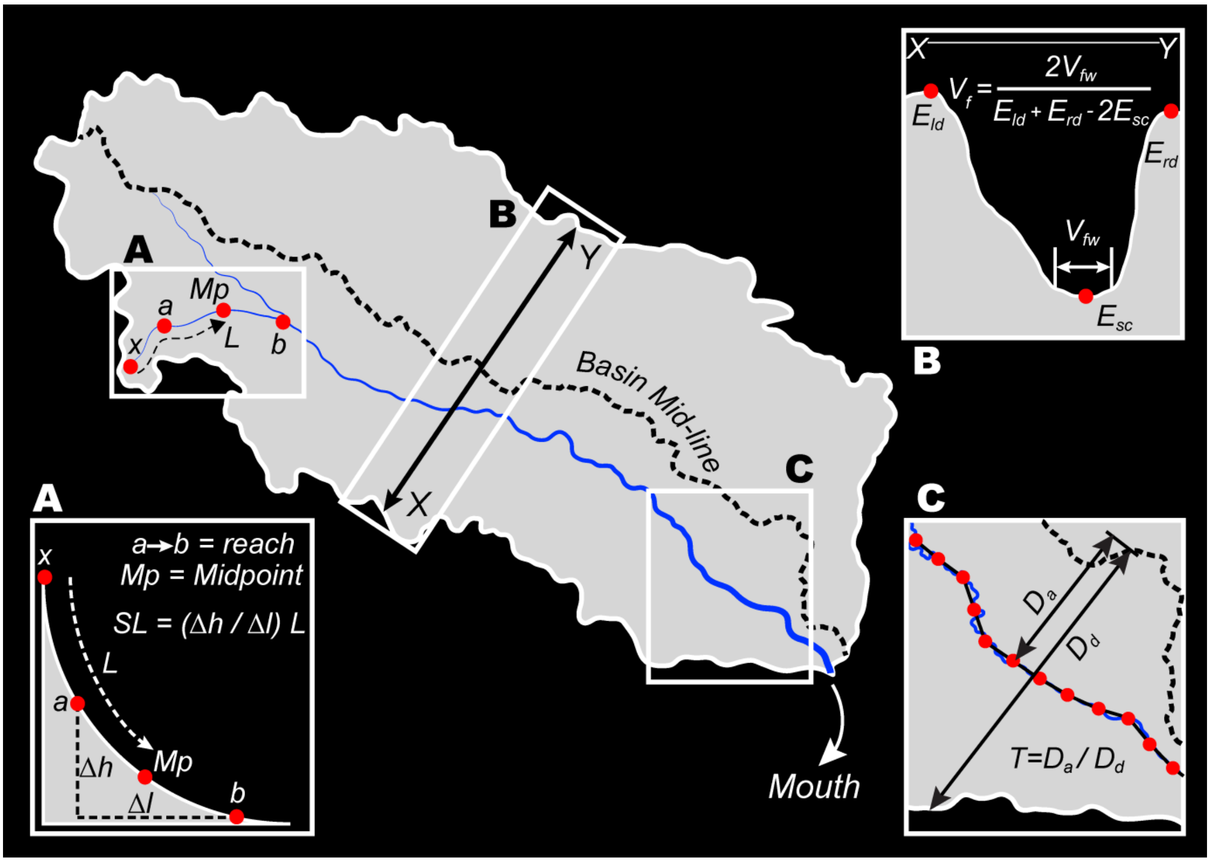


**Figure 1.3.** Hypothetical drainage basin indicating some of the variables that can be extracted in numerical form to be utilized as input for morphometric analysis.

## 1.1.4 Geomorphic indices for morphotectonic analysis

River network parameters and landscapes inherited by geomorphic processes can be defined numerically allowing quantitative analysis of topography and is collectively termed geomorphometry (Pike, 1995; Pike, 2000; Jordan, 2003; Rasemann et al., 2004; Hajam et al., 2013) (Figure 1.3). Morphometry is defined as the quantitative measurement of landscape shape. Landforms can be characterized in terms of size, elevation (maximum, minimum, or average), and slope. Quantitative measurements facilitate comparison of different landforms and to calculate less straightforward parameters defined as geomorphic indices that are useful to identify particular characteristic of an area such as level of tectonic activity. Geomorphic indices and geomorphometry are reconnaissance tools to quantitatively analyze spatially distributed landscapes in order to identify and evaluate areas experiencing rapid tectonic deformations (Keller and Pinter, 1996).

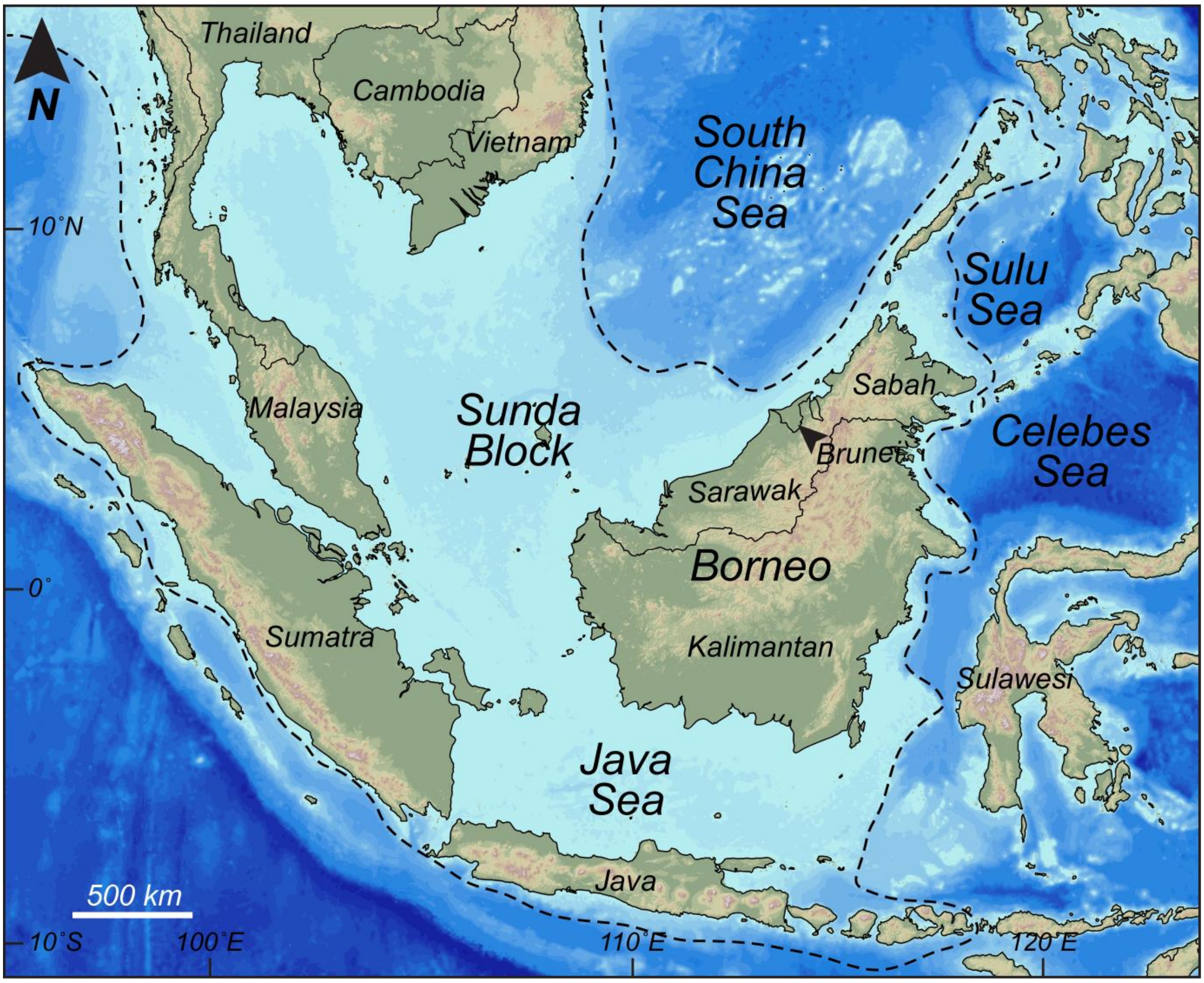


**Figure 1.4.** The Sunda Block. Approximate limit is shown in black dashed lines.

Geomorphic expressions and drainage response due to impact of tectonics on onshore Sarawak, Borneo are poorly understood and research pertaining to geomorphology are scanty. This thesis addresses the geomorphic evolution of north and central Sarawak through

morphometric analysis in order to draw inferences on active tectonics; making this research the first of its type in this region. Consequences of active tectonics, ultimately affecting sedimentation and preservation, are discussed with the aid of conceptual models.

## 1.2 The Drainage Basins of North and Central Sarawak, Borneo

Sarawak is one of the states belonging to Malaysia and is located on the Borneo Island. The east Malaysian state forms the northwest Borneo segment and borders the Malaysian state of Sabah to the northeast, the Indonesian state of Kalimantan to the south and surrounding the independent state of Brunei (Figure 1.4). The continental margin of Sarawak forms part of the Sunda Shelf, which structurally connects Borneo with East Malaysia and the rest of

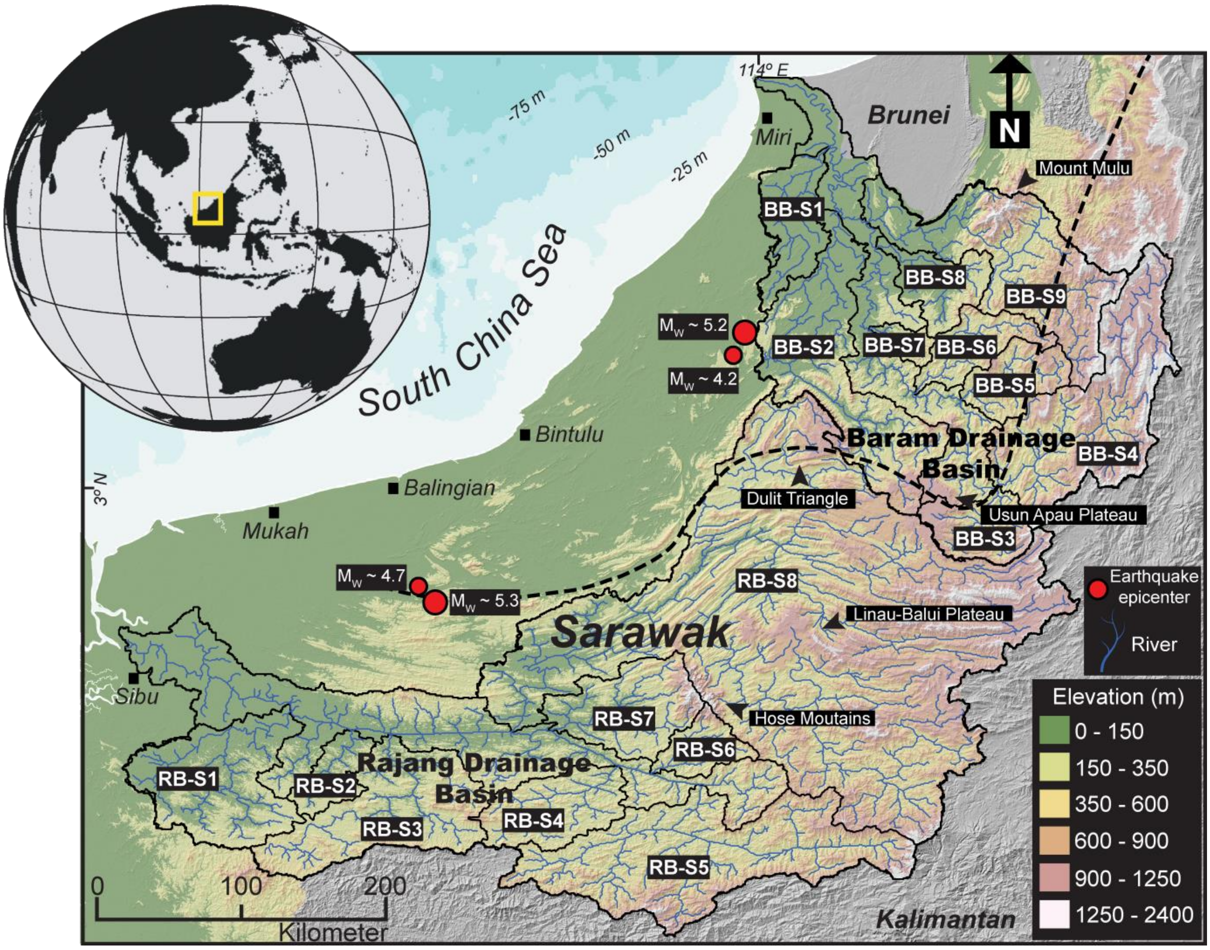


**Figure 1.5.** The Rajang and Baram drainage basins and also shown are the sub-catchments.

continental Southeast Asia (Figure 1.4). N. S. Haile, one of the forerunners of extensive geological work in Borneo, divided Sarawak into zones based on their geological history (Haile, 1974). The Miri Zone to the north, the central part is called the Sibu Zone; the third

division is the Kuching Zone and the fourth division which is termed the West Borneo Basement. According to Hutchinson (2005) the name of the fourth zone is a rather misleading term and falls in the Indonesian state of Kalimantan. This research focuses on geomorphic evolution by implementing topographic analysis and fluvial geomorphology techniques on two of the largest drainage basins of Sarawak: the Baram and Rajang Drainage Basins respectively (Figure 1.5). The drainage network of these basins drain entire north and large areas of central Sarawak. The Rajang River flows for ca. 563 km and drains a total area of ca. 50,000 km$^2$ of central Sarawak whereas the Baram River flows for ca. 400 km and drains a total area of ca. 22,100 km$^2$ of north Sarawak. These river systems are highly influential on sediment distribution in the southern South China Sea margin. The headwaters of Rajang and Baram basins emerge from the Central Borneo Massif that consists mainly of Cretaceous to

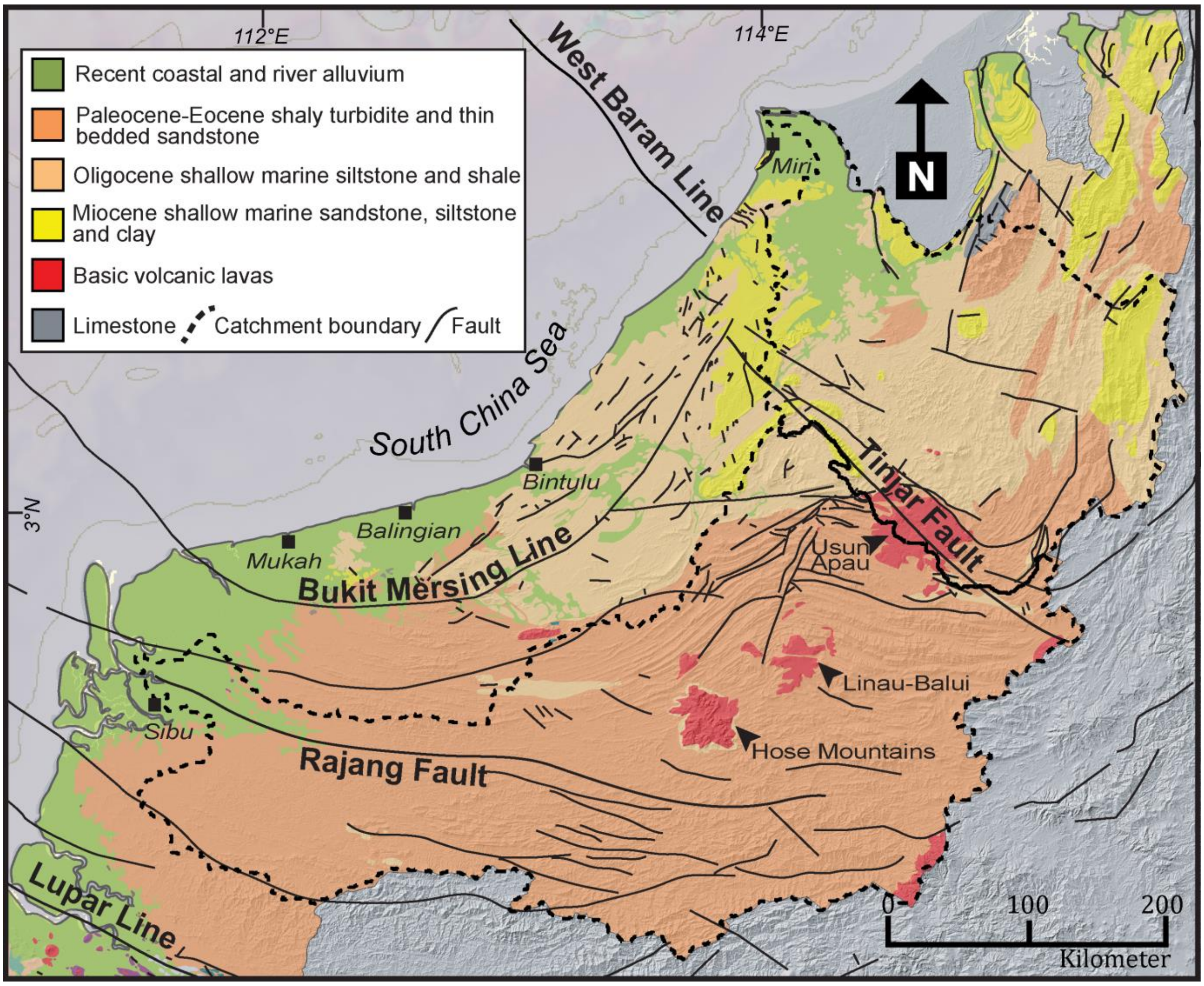


**Figure 1.6.** Simplified Geological Map of Sarawak, north Borneo.

Eocene folded and faulted clastic rocks (Figure 1.6; Wang et al., 2014). These clastics are accretionary complexes and forearc basin sediments that were deposited during the Tertiary opening and spreading of the South China Sea (Staub et al., 2000). Igneous extrusive and intrusive rocks are present and much of the sedimentary rocks are highly metamorphosed (Lam, 1988). Hill slopes are steep and flood plains represent very limited areas. Soils in both basins are poorly developed, representing the mineral composition of the parent materials (Scott, 1985). The average monthly sediment discharge rate for the Rajang River basin is 3600 $m^3$/s (Staub et al., 2000) while the Baram basin delivers at an average, 1445 $m^3$/s of sediments monthly to the South China Sea (Hiscott, 2001).

## 1.3 Problem Statement

The tectonically complex Borneo continent is enveloped by vastly inaccessible tropical rainforests, mountains and deep valleys. Most parts of central and north Sarawak remain inaccessible due to extensive tropical rainforest and peat swamp cover resulting in poor rock exposures. Elements of the tectonic evolution of Borneo such as timing of deformation events, uplift and erosion are still poorly understood (Hall and Nichols, 2002). Geomorphology and evidences of tectonic processes onshore Sarawak is inadequately analyzed. Investigation of morphotectonics and understanding the present day geomorphological configuration of the region could assist in envisaging the processes responsible for shaping the present day topography and ultimately, shedding light on the controls on sedimentation pattern and, preservation of sediments both onshore and offshore. Through this research, an attempt has been made to analyze active tectonics utilizing geomorphometry and validation of results through conventional field techniques in order to obtain valuable insights on neotectonic events that reconfigured the topography of Sarawak. The results and onshore conceptual models produced herewith would provide new insights on recent and active subtle tectonic events. The onshore models could be considered as analogues to offshore architecture of north Borneo and could be beneficial for oil and gas exploration strategy.

## 1.4 Research Questions

This research will address the following questions:

**i.** What are the processes responsible for sculpting the present-day geomorphic expressions in Sarawak?

**ii.** What is the present state and stage of the landscape with regard to topographic evolution?

**iii.** Which regions are affected the most by forces accountable for a dynamically altering landscape?

**iv.** What are the consequences of the altered topography in terms of sedimentation pattern and preservation?

## 1.5 Aims and Objectives

The main aim of this thesis is to investigate geomorphology and morphotectonics of central and north Sarawak utilizing geomorphometric analysis and field evaluation in order to obtain insights on active tectonics and consequent topographic adjustment.

The specific objectives of this study are:

**i.** To conduct morphotectonic analysis of Sarawak through geomorphometry and geomorphic indices.

**ii.** To understand the current stage of landscape development of north Borneo based on results obtained from geomorphometry and gather field evidences (where accessible) to support the results.

**iii.** To produce conceptual models defining present-day topographic and sub-surface architecture of Sarawak describing how sedimentation patterns fluctuated over time and the factors responsible for high denudation rates in the Quaternary.

## 1.6 Thesis Outline

The main body of the thesis is four chapters (2 – 5) describing the geomorphology and morphotectonic analysis of north Borneo. Chapter 2 discusses the literature of the geodynamic framework of the Tertiary Sundaland including the geological, tectonic and geographic characterization of Borneo. The chapter also discusses the geologic and stratigraphic framework of the study area and the general topographic characterization of Sarawak. Chapter 3 discusses the evaluation of active tectonics in Sarawak using morphometric parameters. Chapter 4 presents the analysis and results highlighting the current stage of landscape development of north Borneo. Chapter 5 provides insights into the landscape development of north Borneo using conceptual models and the factors responsible for the onset of a strong erosional regime in the Quaternary. In chapter 6 the conclusion and recommendations for further studies are presented with clear restatement of the main findings of this study.

## 1.7 Summary

This chapter has outlined the overview of project and study area of north Borneo. It has also drawn attention to the key objectives and research question of the study which focuses on the processes responsible for the geomorphic expressions seen today in north Borneo and the current stage of geomorphic development. It also highlighted the problem statement to attempt to understand the geomorphology and topographic signature of the study area situated in largely inaccessible tropical rainforest cover and hostile rugged mountainous terrain, making this thesis the first of its kind in the study area.

# *Chapter* 2

# The Geodynamic Framework of Tertiary Sundaland

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***Contents***



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The Sundaland is the continental core of SE Asia, constituting Indochina, Thai-Malay Peninsula, Sumatra, Java, Borneo and the shallow marine 'Sunda Shelf' between them. Sundaland comprises of numerous Cenozoic sedimentary basins, which developed during the Paleogene and the Middle Miocene (McKenzie, 1978; Whittle and Short, 1978; Fulthorpe and Schlanger, 1989; Hutchison, 1989; Hall and Nichols, 2002; Hall and Morley, 2004; Hutchison, 2004; Hall et al., 2008; Metcalfe, 2011). To the south and southwest the oceanic crust of the Indian plate and the southeast Australian continental crust forced the collision of eastern Indonesia with the Sundaland margin causing subduction along the Sunda-Java Trench. (Hall and Morley, 2004; Hutchison, 2004). Recent researches on the Sundaland sedimentary basins and their settings have been documented by several authors (Morley, 1991; Sandal, 1996; Longley, 1997; Morley, 2001; Hall, 2002; Morley, 2002; Hall and Morley, 2004; Pubellier and Morley, 2014). Perhaps, the most remarkable and unusual basins within Sundaland are those in the central region. This region stretches from North Borneo to Southern Laos and is composed of Cenozoic sediments. The present day tectonic elements of

Southeast Asia were shaped by complex extensional and compressional interactions during the Cenozoic Era involving three tectonic plates. They are the continental Philippine tectonic plates to the northeast, the oceanic Indian-continental Australian tectonic plate to the south and southwest and finally, the oceanic Pacific tectonic plate to the east. The collision belts, marginal seas, island arcs and micro-plates are the result of these complex interactions (Sandal, 1996; Franke et al., 2014; Pubellier and Morley, 2014; Savva et al., 2014). The Borneo region occupies a central position in Sundaland, bounded by the South China Sea to northwest, the Sulu Sea and Celebes Sea to the east and the north-east part of Sundaland to the South within the zone of lithospheric deformation (Hall and Morley, 2004). The extrusion of continental fragments from Asia driven by India's collision and effects of collision of Australia with SE Asia have all been implicated in the development of Borneo.

## 2.1 Geological, tectonic and geographic characterization of Borneo

Borneo is one of the largest islands in the world but the geology of the area is poorly known because of difficulties of access to the tropical rainforest of much of the interior, a lack of reliable dating of igneous rocks, poorly fossiliferous sedimentary rocks and an absence of coherent stratigraphic scheme for many parts of the island. To the north and NE of Borneo are three deep basins (South China, Sulu and Celebes Seas) and to the east is the narrow Makassar Strait. The continental margins of all of these areas have relatively narrow shelves before descending to depths of several kilometers. In contrast, to the west and south is the Sunda Shelf, an area of very shallow depths connecting Borneo to Indochina, peninsula Malaysia and Thailand, Sumatra and Java. Much of the Sunda Shelf was emergent at intervals during the Pleistocene and probably during significant periods of the Cenozoic (Figure 2.1). A land connection between southern Borneo and mainland Southeast Asia is believed to have been present during the Eocene and Oligocene (Pupilli, 1973). A large river considered to possibly be the ancestral Mekong River ran across the length of Sundaland from its Eurasian source with a delta in the Natuna Island during the Late Cretaceous-Early Tertiary (Moss and Chambers, 1999).

Borneo is the result of Mesozoic accretion of ophiolitic, island arc crust and microcontinental fragments of south China and Gondwana origin, with their sedimentary cover, onto the Palaeozoic continental core of the Schwaner Mountains in the SW of the island (Figure 2.2; Hutchison, 1989; Metcalfe, 1998). The Schwaner Mountains consist of Paleozoic metamorphic rocks intruded by Cretaceous granites and tonalities, and this zone formed part

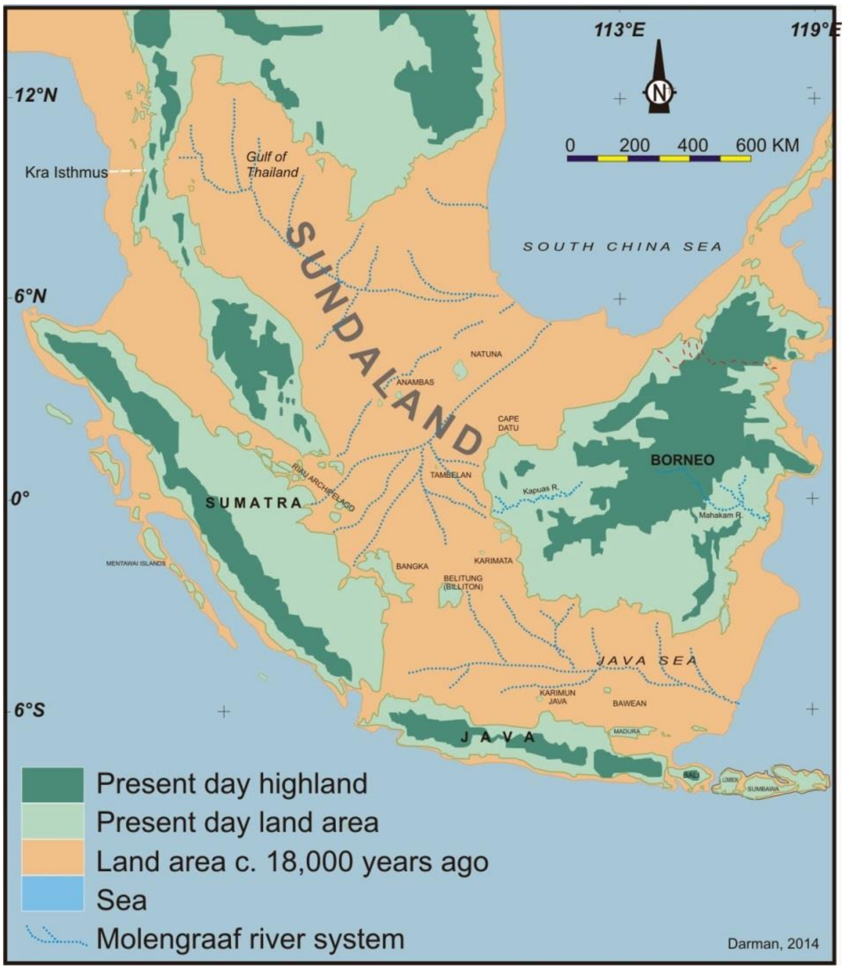


**Figure 2.1.** Map of Sundaland showing land area during the Last Glacial Maximum. Figure source: http://phsyiography-indonesia.blogspot.fr/2014/08/sundaland.html.

of the stable Sundaland craton during the Mesozoic and Cenozoic. Pre-Tertiary rocks occur in the southwestern and eastern parts of Borneo and from northeast to southwest across the island. The SW Borneo continental terrain is intruded by a belt of Schwaner Mountains granite batholiths (ca. 100-130 Ma) (Williams et al., 1989), which are the exhumed deeper parts of a volcanic arc that formed above a South-dipping subduction of the ‘Proto-South China Sea’ oceanic plate. Permo-Triassic schists, gneisses, granites, gabbros and serpentinites also crop out at the eastern and western ends of the Ketungau Basin (Figure 2.2) (Pieters and Supriatna 1990; Wilson and Moss, 1998). Much of the Central Kalimantan Ranges are composed of Upper Cretaceous to lower Tertiary turbidites of the Rajang and Embaluh groups and they have also been intruded by Cretaceous granites in places (Pieters and Supriatna, 1990). The lithologies of Central Kalimantan ranges have been interpreted to have an accretionary prism origin by Hamilton (1979). However, Moss (1998) was of the opinion, that the turbiditic lithology was a remnant oceanic basin depositional setting byproduct.

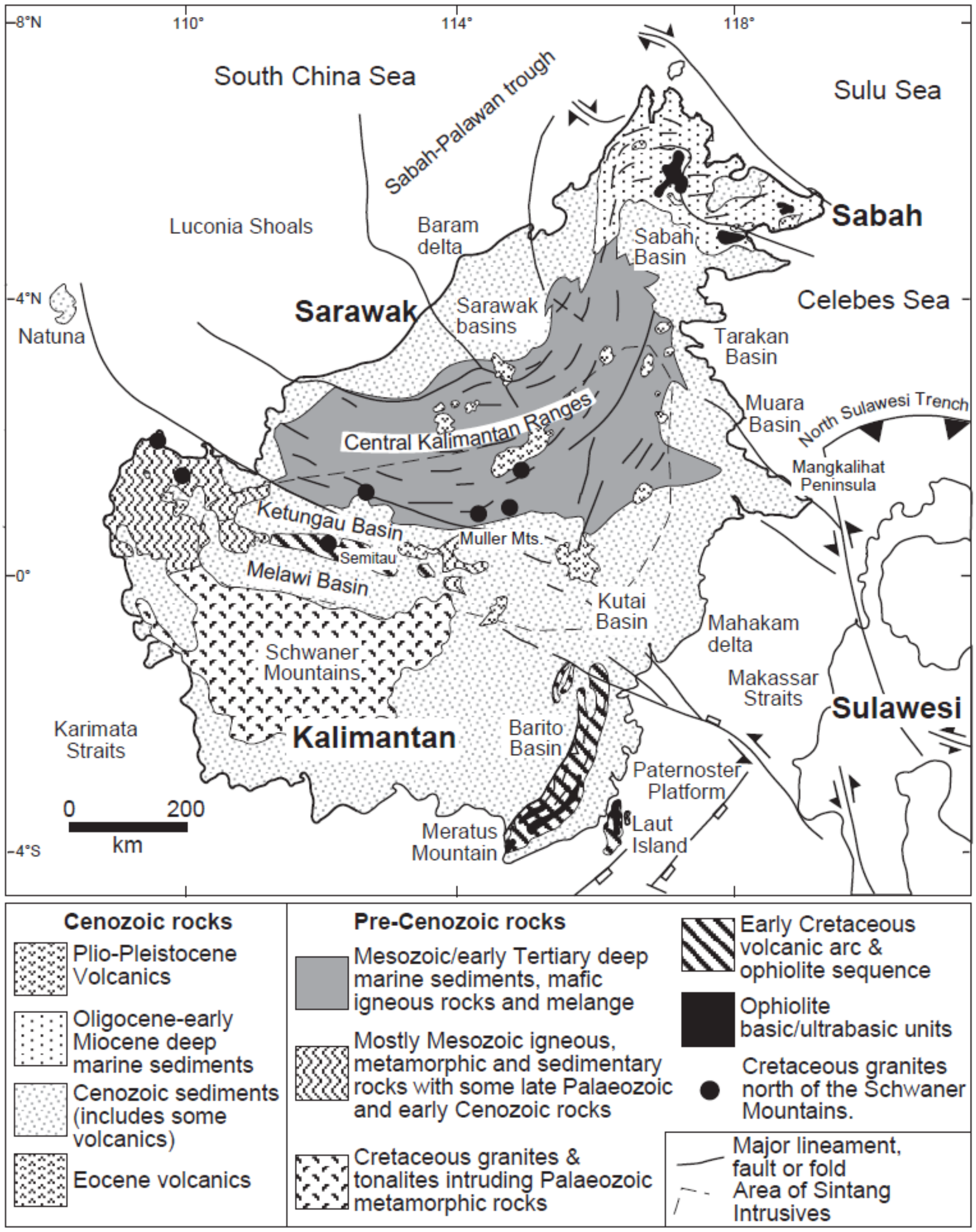


**Figure 2.2.** Simplified geological map of Borneo (Moss and Wilson, 1998).

Cretaceous shelf sandstones, limestones, Triassic granites and older metamorphic rocks can also be witnessed in central Borneo (Hutchison, 2005). Similarities between the pre-Cenozoic rocks of western Sulawesi and east Kalimantan suggest that they were accreted onto the eastern margin of Sundaland before the Cenozoic. At the beginning of the Cenozoic Borneo formed a promontory of Sundaland at the eastern margin of Eurasia, partly separated from Asia by oceanic crust of proto-South China Sea. Tertiary sedimentary rocks cover major portions of eastern, central and northern Borneo, which were deposited in lacustrine, fluvial marginal-marine and/or marine settings. The depocenters were often laterally interconnected through local intricate and narrow links. Tertiary sediments rest unconformably on variably deformed pre-Tertiary units (Wilson and Moss, 1998) and earlier basement structures influenced basin evolution (Cloke, 1997). A period of Paleogene extension and subduction which commenced in the middle Eocene was subsequent to contemporaneous Tertiary sedimentation (Moss and Finch, 1998; Moss and Chambers, 1999). The onshore geology of north Borneo is punctuated by a series of W-E to SW-NE trending accretionary complexes, composed of intensely folded, predominantly South-dipping, imbricate deep water sediments of Early Cretaceous to Middle Miocene age, with fragments of ophiolitic rocks. During the early Neogene there was orogeny, denudation and change in sedimentation patterns throughout much of Borneo (Hutchison, 1989; Tan and Lamy, 1990; van de Weerd and Armin, 1992; Hazebroek and Tan, 1993; Moss and Chambers, 1999).The closing of the proto South China Sea basin was probably diachronous, and was punctuated by microplate collisions, like the Luconia/ Miri Block collision, which caused a Middle-Late Eocene uplift event in onshore north Borneo. By the end of Early Miocene, after collision of the Dangerous Grounds – Palawan Block, the subduction and arc volcanism ceased completely. This also stopped the opening of the South China Sea, causing uplift across much of north Borneo-Kalimantan, leading to progradation of deltas around Early-Middle Miocene boundary in Sarawak and Kalimantan.

At the beginning of the Miocene, the sprawl of the island above prevalent sea level was substantially smaller, and marine deposits covered much of north Borneo (Hamilton, 1979; Moss and Chambers, 1999). Intense tectonism during this time resulted in compression that was dominant in large parts of north and central Borneo causing strong folding and thrusting initiated through basement uplifts and wrench faulting (Darman et al., 2000). As a result of this orogeny and plate tectonic reorganization, more land surface area emerged as major deltas prograded outwards. The increased loading of areas close to Borneo could then have further contributed to rates of uplift of the central mountain ranges by flexural effects (Hall and Nichols, 2002). The northern parts of Borneo experienced a phase of deformation triggered by trough basement uplifts and wrench faulting during the Pliocene (Darman and Damit, 2003). Evidences of folding and thrusting as results of these tectonic stages were reported previously (Cullen, 2010; Menier et al., 2014). The increased elevation of orogens and exposure of more land area would have influenced the climate in the region from an Oligocene dry climate to an ever-wet climate of the Neogene in Borneo (Morley, 1998).

However, Borneo has had a similar climate from the Neogene up until present-day (Hall and Nichols, 2002). In the Early Miocene there was a significant change in the character of sedimentation around Borneo. Large amount of clastic sediments began to pour into the deep basins to the north and east of the island and major delta system formed which prograded rapidly away from the island (Hall and Nichols, 2002; Hall, 2013). The only possible source for the sediment is Borneo itself. Although some of the Paleogene sediments in Borneo could have been supplied by river systems from Indochina (Hutchison, 1989; Hall, 1996; Hutchison, 1996; Hutchison et al., 2000), by the Early Miocene the South China Sea would have been a barrier to sediment supply from the north and sediment that was transported south from Asia was deposited in the Gulf of Thailand and the Malay Basin (Balaguru and Nichols, 2004).

The Neogene sediments in the basins around Borneo can provides some estimates of the amount and timing of uplift in the mountains of the island (Tongkul, 1994). From publish and unpublished information including observations made by the SE Asia Research Groups, it seems that much of the sediments in the north Borneo basins was derived initially from erosion of Paleogene sediments and later from cannibalization of the older Neogene sediments during inversion of the prograding deltas (Sandal, 1996; Moss et al., 1998; Moss and Wilson, 1998; Hutchison et al., 2000). No detailed studies of petrography or provenance have been made in most areas but the Neogene sediments seem to be relatively mature, quartz-rich clastic rocks with some evidence of local clastic contributions from elevated nearby basement rocks (Hall and Nichols, 2002). Hutchison, (Hutchison, 1996) remarks that “an interesting heavy mineral provenance study remains to be carried out” in Sabah this is the case elsewhere in Borneo.  Tanean et al. (1996) reported that Lower Miocene sandstone is moderately quartzose with a moderate lithic component, and a subsidiary but significant volcanic lithic component that records continuous volcanic activity during the Early Miocene. Uppermost Lower-lowermost Middle Miocene sandstone is volcanogenic, recording an increase in volcanic activity in the western Kalimantan between 17 and 14.5 Ma. Middle and Upper Miocene sandstone are highly quartos and are recycled products of basin inversion events to the west and recorded no evidence of volcanic activity (Moss et al., 1998; Hall and Nichols, 2002).

The Borneo Island has an area of 743,330 km2 and is a region of rugged terrain (Figure 2.3). Although most of the central mountains are below 2500 m, there are about a dozen peaks of

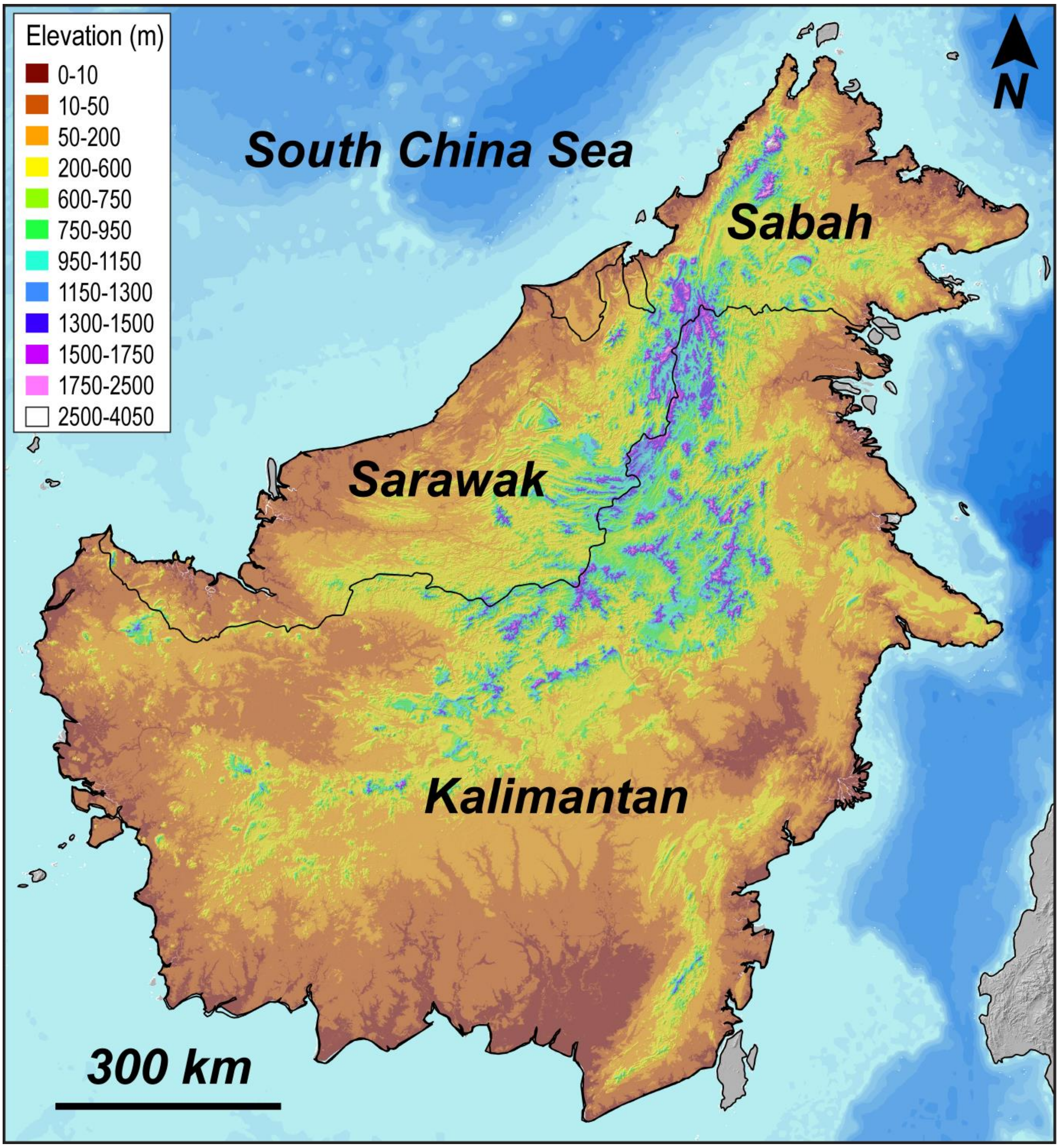


**Figure 2.3.** Shaded relief map of Borneo showing diverse variations in altitude.

about 2500 – 3000 m, mostly in the half of the island north of the equator. The highest peak is Mount Kinabalu (4101 m) in the extreme north in the Malaysian state of Sabah. Thus, on a global scale Borneo is not an island of major mountains and although the present area of highlands and mountains is large, at about 450,000 km2, most of this area (about 95%) is well below 1000 m in height.

The climate of Borneo is tropically hot and humid along the coast as it geographically lies on the Equator. The temperatures are fairly uniform, averaging 27 – 33° C during day time and rarely dropping below 20° C at night with a relative humidity of around 80 % for much of the year. The mountainous areas have a cooler climate and temperatures may drop below 20° C at night. Annually Borneo averages from 2540 – 4060 mm yr-1 of rainfall with two monsoon seasons. The climate is affected by the weather patterns of the South China Sea, Sulu Sea and Sulawesi Seas and the seasonal winds can bring either warm dry weather or heavy rains depending on their nature and origin.

## 2.2 Geologic framework of Sarawak

In 1960, the geology of Sarawak, Brunei and the western part of North Borneo was studied in detail by Liechti and his group (Liechti et al., 1960). This work was compiled from the Royal Dutch Shell Group of Companies in the British Territories in Borneo and from various publications by Liechti, in association with Roe and Haile (1960). They pioneered the geological understanding of Borneo. They generated structural, tectonic and geomorphological maps based on extensive traditional outcrop and topographic observations. The initial estimation of stratigraphic ages, regional and local unconformities were done by his group. They also conducted photo-geological re-interpretation of the Bintulu area, Central Sarawak and named the formations.

Following the preliminary geological works conducted in Sarawak by Liechti and his team; N. S. Haile (1968) was among the first workers to attempt to fit the region into the geosynclinal theory. A geosyncline, according to Whitten and Brooks (1972), is a major sedimentation and structural unit of the crust. Depending on the type and characteristic of the rock strata of the orogenic system, geosynclines can be divided into miogeosyncline consisting of limestone and clastic sedimentary rocks and eugeosyncline comprising of deep marine sediments and abundance of volcanic rocks. Through the geosynclinal theory, Haile, he tried to understand the tectonic framework of Sarawak and proposed the famed 'Northwest Borneo Geosyncline'. He classified thirty two formations as eugeosynclinal, miogeosynclinal and isolated basin formations. He also subdivided all the geological formations in North-west Borneo into four groups namely: Brunei Group, Plateau Group, Baram Group and Rajang Group. Haile suggested the eugeosynclinal furrow was represented by the Rajang group deposits whereas the miogeosynclinal ridge was represented by the Bukit Mersing spilitic pillow lavas, spilite and radiolarian chert at Usun Apau Plateau and limestones in the upper Baram Valley. The Tertiary sediments represented by the Baram Group were interpreted to be deposited within the miogeosynclinal furrow (Haile 1968) (Figure 2.4).

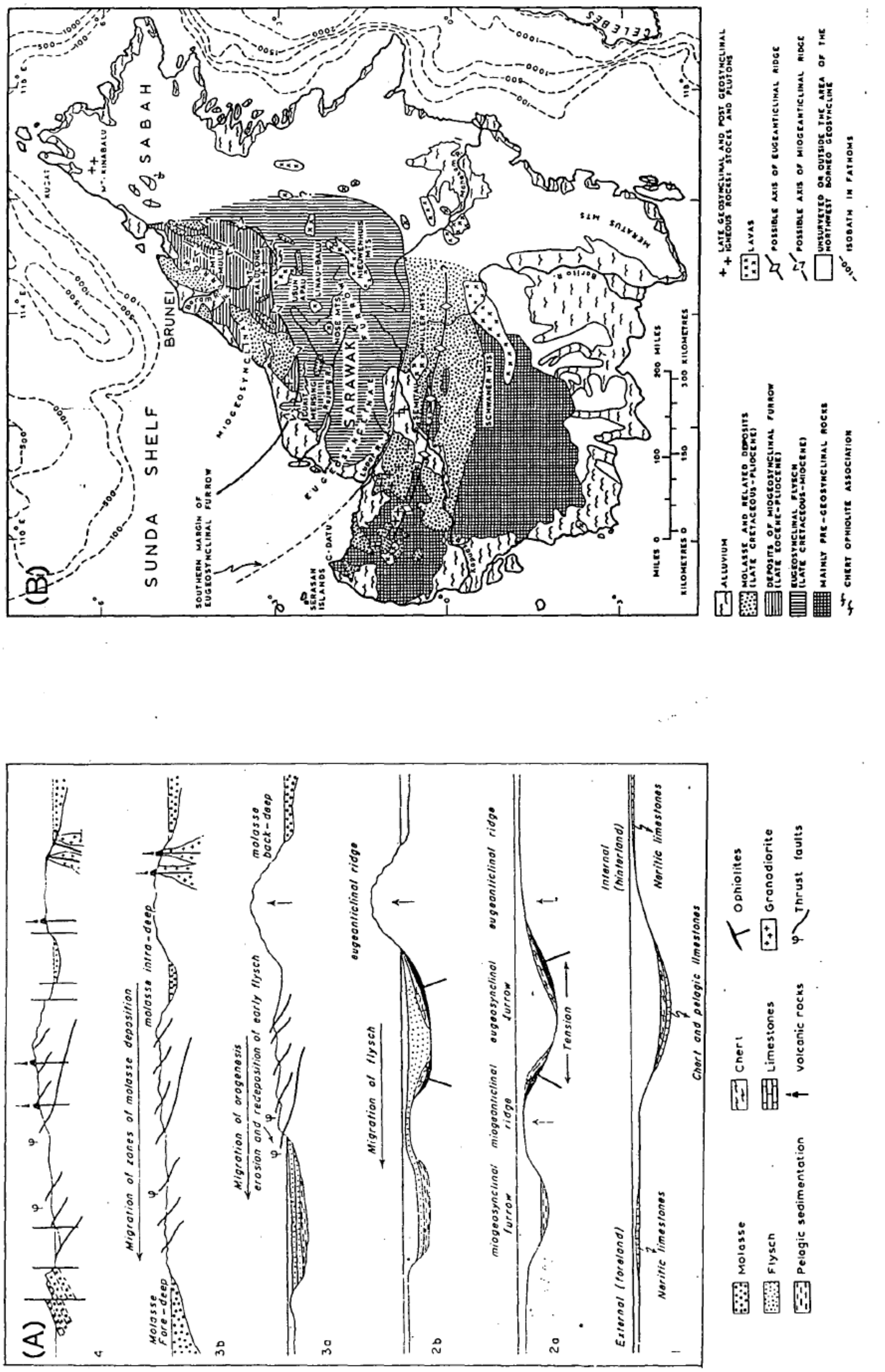


**Figure 2.4.** The Northwest Borneo Geosyncline (Haile, 1968).

Sarawak can be divided into four zones according to their geological history (Haile, 1974). The most northerly is the Miri Zone, dominated by shallow marine shelf sediments that were deposited upon older continental crust. The boundary between the Miri Zone and Sibu Zone is Bukit-Mersing Line (Hutchison, 1989) (Figure 1.6). The Sibu Zone is in the central part of Sarawak that is dominated by thick shale-sandstone turbidite sequences deposited upon oceanic crust. The rocks were uplifted in Late to Middle Eocene (William & Harahap, 1987; Hutchison, 2005) time. The boundary between the Sibu Zone and Kuching Zone is the Lupar Line (Tan, 1979). The Kuching Zone located to the southwestern part of Sarawak consists of Jurassic – Cretaceous shelf deposits, molasses and related non-marine deposits on the edge of the West Borneo Basement Complex (Haile, 1974; Hutchison, 2005). The most southerly zone is the West Borneo Basement (Haile, 1974) composed of Carboniferous – Permian basement rocks intruded by Cretaceous volcanic and plutonic rocks (William et al., 1988).

The drainage network of the watershed basins studied in this research drain entire central and north Sarawak.

## 2.3 Stratigraphy of central and north Sarawak

In central Sarawak, the oldest formation at the base of the Rajang Group is the deep marine turbidites of the Belaga Formation that began to be deposited during the Late Cretaceous and ended in the Eocene by the Sarawak Orogeny (Figure 2.5; Leichti et al., 1960; Wolfenden, 1965; Hutchison, 1986; Mazlan, 1999; Kamaluddin Hassan, 2004; Hutchison, 2005). The Belaga Formation is highly deformed with steeply dipping shaly turbiditic rocks as a result of being compressed, uplifted and sheared when Sundaland and the Luconia blocks collided. This collision led to the subduction of the Rajang Sea beneath the South Borneo Block that uplifted the Belaga Formation (Adam, 1965; Hutchison, 2005). The Belaga Formation is surrounded by the younger formation, i.e. Tatau Formation and Nyalau Formation along the Anak-Nyalau Fault contact. Most of the Ransi Member conglomerate exposure is near the contact of Belaga Formation.

The Middle Eocene to Oligocene Tatau Formation is estimated to be made up of over 2,500 m of clastic sediments (Kamaludin Hassan, 2004; Leichti et. al., 1960; Wolfenden, 1960). The oldest unit of Tatau Formation is the Ransi Member. It is exposed in Tatau area at Ransi Hill, Tatau Hill, and Tutong Hill. It is made up of about 20 to 30m of moderately thick

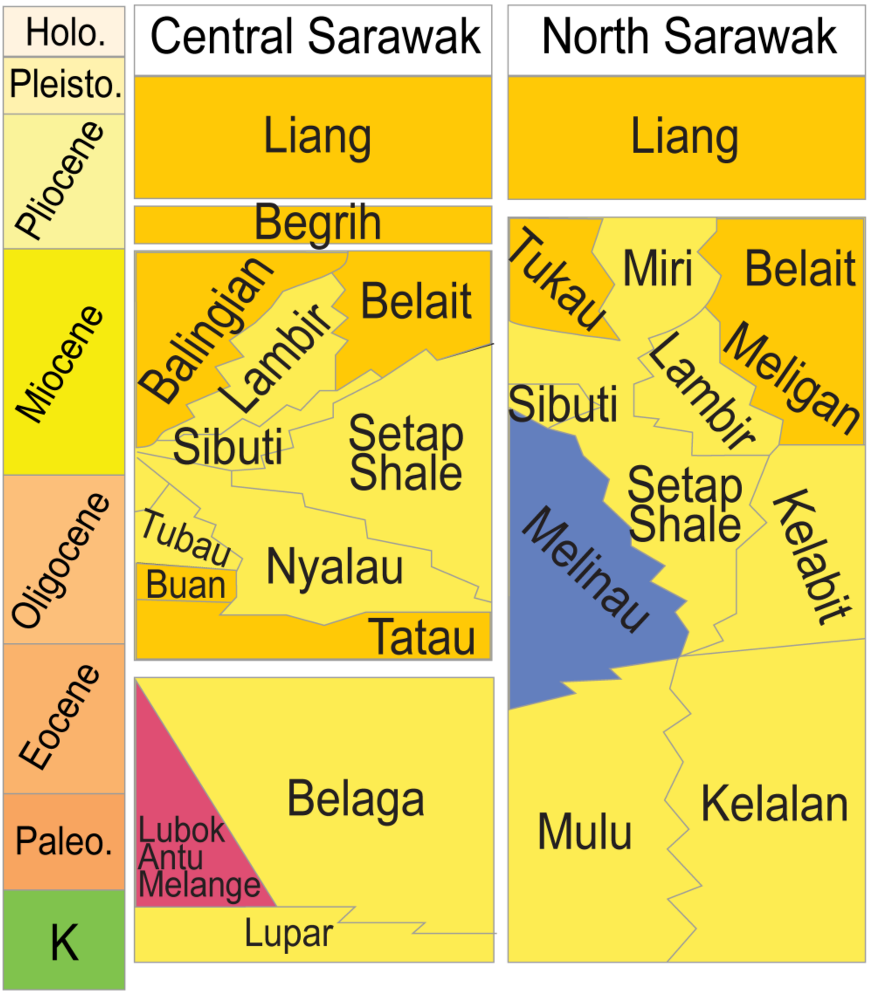


**Figure 2.5.** Generalized stratigraphy of central and north Sarawak.

bedded (1-2m) sandy conglomerate and sandstone with very thin bedded, light to dark grey shale.

The Ransi Member is made up of 3 lithofacies: (1) thick bedded, coarse grained conglomerate in the lower part; (2) thin to medium bedded coarse grained, bioturbated sandstone in middle part and (3) medium grained, cross bedded sandstone in the upper part. The lower contact with the underlying Belaga Formation is an angular unconformity while it grades upward into the rest of Tatau Formation.

The Buan Formation conformably overlies the Tatau Formation and overlying Nyalau Formation. This Formation is predominantly shaly and contains thin beds of siltstone and fine to medium grained sandstone (Hutchison, 2005).

The Nyalau Formation of Oligocene – Miocene age consists of hard fine to medium grained sandstones alternating with shale (Hutchison, 2005) and overlies the Buan Formation. Coal beds are frequently encountered in the Formation. The sandstones have cross-bedding and show ripples. Burrows of Ophiomorpha are common (Siddiqui et al., 2014). The Nyalau Formation was interpreted to have been deposited in a shallow marine environment ranging from coastal plain to estuarine, shallow littoral to inner neritic. The total thickness of the Formation is estimated to be 5000-5500 m (Hutchison, 2005). To the east, the Nyalau is conformably overlain by the Sibuti and to the northeast it interfingers with the shaly Setap Shale.

In the central and north Sarawak, The Sibuti Formation, as described by various authors (e.g. Liechti et al., 1960; Wilford, 1961; Haile, 1962), is mainly comprised of clay and shale with subordinate siltstone and limestone. Liechti et al. (1960) interpreted an inner neritic depositional environment for the Sibuti Formation, with possible extension into a shallower environment, based on the presence of ripples. The Setap Shale Formation is a thick, extensive and monotonous succession of shale with subordinate thin sandstone beds and a few thin lenses of limestone. The common lithologies consist of grey shale, mudstone, sandstones and a few limestones. In the north zone of Sarawak the Setap Shale Formation makes a change to the very sandy Lambir Formation. The Miocene Formation found even in the central zone comprises of sandstone, shale and some limestone. The maximum thickness of the formation is estimated to be around 1600 m (Hutchison, 2005).

In the central zone the Balingian Formation rests unconformably on the Lambir Formation and unconformably overlain by the Begrih Formation. The Balingian Formation is a thick sequence of sandstone, pebbly sandstone, fossiliferous mudstone with abundant coal and lignite. The Formation is interpreted to be deposited in an estuarine to lagoonal environment. Whereas in the north zone, the Lambir Formation is overlain by the Miri Formation which is mainly argillaceous in the lower parts and dominated by sandstones in the upper part (Abieda, 2005).

The Balingian Formation in the central zone is unconformably overlain by the Pliocene age Begrih Formation. This Formation consists of a succession of laminated sandstones, fine sandstones, ortho-conglomerate, sandy conglomerate, coal and peat, clays and locally a boulder conglomerate at the base (de Silva, 1986). The Begrih Formation is mainly fluviatile and non-marine and contains abandoned channel deposits. The Formation is conformably overlain by the Liang Formation which consists of successions of clay and sand with abundant lignite and some tuff. The environment of deposition of the Liang Formation is interpreted to be coastal plain to shallow marine (Hutchison, 2005).

The Balingian, Begrih and Liang Formations host major coal beds which are important coal mining zones in Sarawak. The brown coals of the Begrih and Liang Formations are humic and were formed in swamps identical to the present-day swamps of NW Sarawak.

## 2.4 Geomorphic Expression

The surficial topography of central Sarawak varies from terrain underlain by recessive shale through zones of linear ridges (interbedded sandstone and shale) to rugged highlands consisting of thick massive sandstones (Light et al., 1994). In the interiors of Sarawak, the landscape is dominated by a wide swath of discontinuous plateaus built of late Cenozoic volcanic and pyroclastic rocks. The Hose Mountain Plateaus (Figure 1.5), consisting of deeply dissected mesa, is about 32 km across rising to 2006 m resting on lower Miocene Nyalau formation equivalent (Kirk, 1957). The Linau-Balui Plateaus covers 290 $km^2$ and rises to 1127 m resting unconformably on folded Belaga formation. It consists of a northern Tableland of 1100 m elevation and a larger southern Tableland of about 820 m elevation. The Usan Apau Plateau is about 906 $km^2$ and rises to 1372 m. The plateau separates a part of the headwaters of the Baram and Rajang rivers (Figure 1.5). The plateau has waterfalls spilling over its rim with plunges of more than 200 m (Hazenbroek and Morshidi, 2001; Cullen et al., 2013). It consists of an eastern Tableland of about 1000 m elevation and a smaller western Tableland of 760 m high (Hutchison, 2005). The mesas have strongly dissected margins with precipitous cliffs and deep marginal embayment. The rivers plunge over the high plateau edges in high cataracts and waterfalls (Hutchison, 2005).

## 2.5 Summary

This chapter has characterized first the geological, tectonic and geographic characterization of the whole Borneo island. The chapter continues to give a detailed view of the geology of the study area: Sarawak and also regarding the stratigraphic units. Finally the chapter concludes with a view of the geomorphology of Sarawak.

*Chapter* 3

# Active Tectonic Deformation along Rejuvenated Faults in Tropical Borneo: Inferences Obtained from Tectono-geomorphic Evaluation

Mathew, M., Menier, D., Siddiqui, N., Kumar, S., Authemayou, C., 2016.
*Geomorphology* 267, 1-15.

## *Contents*

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## 3.1 Abstract

The island of Borneo is enveloped by tropical rainforests and hostile terrain characterized by high denudation rates. Owing to such conditions, studies pertaining to neotectonics and consequent geomorphic expressions with regard to surface processes and landscape evolution are inadequately constrained. Here we demonstrate the first systematic tectono-geomorphic evaluation of north Borneo through quantitative and qualitative morphotectonic analysis (at sub-catchment scale) of two large drainage basins located in Sarawak: the Rajang and Baram basins. The extraction of morphometric parameters utilizing digital elevation models arranged within a GIS environment focuses on hypsometric curve analysis, distribution of hypsometric integrals through spatial autocorrelation statistics, relative uplift values, asymmetry factor and normalized channel steepness index. Hypsometric analysis suggests a young topography adjusting to changes in tectonic boundary conditions. Autocorrelation statistics show clusters of high values of hypsometric integrals as prominent hotspots that are associated with less eroded, young topography situated in the fold and thrust belts of the Interior Highlands of Borneo. High channel steepness and gradients (> 200 m0.9) are observed in zones corresponding to the hotspots. Relative uplift values reveal the presence of tectonically uplifted blocks together with relatively subsided or lesser uplifted zones along known faults. Sub-catchments of both basins display asymmetry indicating tectonic tilting. Stream longitudinal profiles demonstrate the presence of anomalies in the form of knick-

zones without apparent lithological controls along their channel reaches. Surfaces represented by cold spots of low HI values and low channel gradients observed in the high elevation headwaters of both basins are linked to isolated erosional planation surfaces that could be remnants of piracy processes. The implication of our results is that Borneo experienced recent strong tectonic deformation and active folding continues in the Rajang Group fold–thrust belt to present and these events reactivated old major faults and minor related dislocations. From geomorphic analysis associated with sedimentary record, we posit that the terrain could have undergone high uplift rates since 5 Ma or multi-phased uplift with periodic pulses of high and low uplift rates intermittently. The accelerated denudation due to exacerbated precipitation rates owing to orographic effect since 5 Ma allows the topography of Borneo to adjust rapidly to a transient state of geomorphic evolution.

Keywords—morphometric indices; morphotectonics; geomorphic evolution; tectonic uplift; fault reactivation; Borneo

## 3.2 Introduction

The constant interplay of tectonic deformation of the lithosphere and atmospheric forcing constitute the essential components of topography. The records of these forcings may be retained and manifest in fluvial systems that produce consequent erosion and combinedly shape majority of landscapes that envelop the earth's surface. Quantitative and qualitative analysis of such landscapes and the identification of regions experiencing tectonic deformation is made feasible through geomorphologic investigative techniques such as geomorphometry and geomorphic indices (Keller and Pinter, 1996). This approach numerically defines land surface parameters, and therefore have been successfully applied by scientists in locations having thick vegetation cover or arid conditions, in order to characterize landscapes and identify active tectonics of varying magnitudes (e.g., Strahler, 1952; Pike, 1995; Pike, 2000; Chen et al., 2003; Rasemann et al., 2004; Molin et al., 2004; El Hamdouni et al., 2008; Troiani and Della Seta, 2008; Pedrera et al., 2009; Pérez-Peña et al., 2009a; Font et al., 2010; Pérez-Peña et al., 2010; Giaconia et al., 2012; Mahmood and Gloaguen, 2012, Gioia et al., 2014; Giachetta et al., 2015).

Borneo is the third largest island in the World, shared by Malaysia (Sarawak and Sabah), Indonesia (Kalimantan) and Brunei (Figure 3.1). It is characterized by unusually high rates of denudation over the last 20 Ma (average minimum denudation rate of 326 m $Ma^{-1}$) as a result

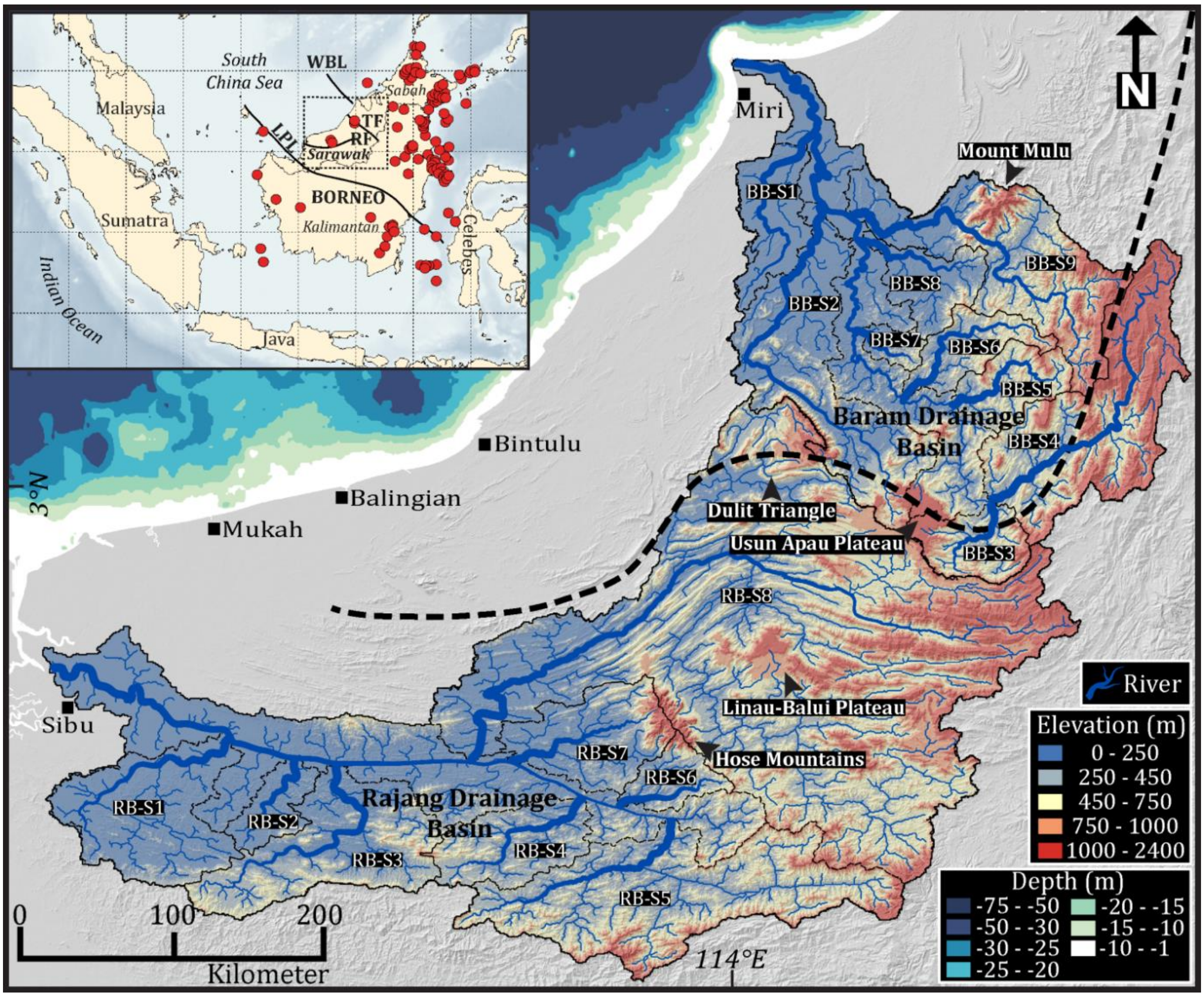


**Figure 3.1.** The two largest catchments of Sarawak, north Borneo: Rajang and Baram basins. Both watersheds drain extensive regions of central and northern Sarawak. Sub-catchments of Rajang basin (RB-S1 – RB-S8) and Baram basin (BB-S1 – BB-S9) are numbered and catchment boundaries are demarcated by black thin dashed-lines. Drainage patterns are illustrated in blue color. Black thick dashed-line indicates approximate limit of the Interior Highlands of Borneo. Inset map shows the location of major faults: WBL – West Baram Line and TF – Tinjar Fault oriented NNW-SSE in the Baram basin and RF – Rajang Fault running W-E in the Rajang Basin respectively. A major fault LPL – Lupar Line is also shown in the inset. Red circles denote areas of recent seismicity (1960 – 2014).

of plate boundary forces (Hall and Nichols, 2002). Present day seismicity in Borneo indicates a large number of seismic events in onshore and offshore Sabah and Kalimantan (Figure 3.1). On the contrary, Sarawak, bordering Sabah and Kalimantan, indicates a sparse distribution of seismicity occurring from 1960 – 2015 (http://earthquake.usgs.gov/earthquakes/) (Figure 3.1) and is considered to experience an intra-plate setting since at least Late Miocene. A large number of works have confirmed the incidence of important Late Mio-Plio-Quaternary tectonic events in the offshore and coastal regions of northwest Borneo (e.g., Cullen, 2010;

Kessler, 2010; Kessler and Jong, 2011; Cullen, 2014; Mathew et al., 2014; Menier et al., 2014; Pubellier and Morley, 2014). However, in the onshore interior parts of Borneo, studies pertaining to possible recent and/or present-day tectonic activity and the consequent geomorphic expressions with regard to surface processes and landscape response to forcings are inadequately constrained. Recent studies involving outcrops and near-shore seismic sections have shown tectonic activity locally during the Pleistocene/ Holocene border (Kessler and Jong, 2011; Kessler and Jong, 2014). GPS velocities gathered by Simons et al. (2007) indicate active movements against or along at least few segments of the Tinjar fault in the order of 3 mm $yr^{-1}$ (Figure 3.1).

Here we investigate and evaluate the occurrence of neotectonic events and consequential deformation, and landscape response in northwest Borneo through quantitative and qualitative geomorphic assessment of two of the largest drainage basins located in Sarawak: Rajang and Baram Drainage Basins (Figure 3.1). The main rivers of the two basins drain entire north and central Sarawak. Geomorphic analysis conducted by us focused on sub-catchment scale hypsometric curves (*HC*) and hypsometric integral (*HI*) which has capabilities to potentially reveal complex interactions between erosion and tectonics, and can be significantly correlated to uplift rates (Strahler, 1952; Schumm, 1956; Weissel et al., 1994; Hurtrez et al., 1999, Pérez-Peña et al., 2009b). We then computed relative tectonic uplift values (*U*) utilizing hypsometric integral (*HI*) and calculated the drainage basin asymmetry (*Af*) to identify tectonic tilting of sub-catchments (Keller and Pinter, 1996). Finally, normalized channel steepness index ($k_{sn}$) (Wobus et al., 2006) was calculated in order to identify areas where rivers would respond to tectonic forcing by steeping their gradient and enhancing incision. This index has proved to be efficient in distinguishing zones subject to varying rock uplift rates (Kirby and Whipple, 2012; Castillo et al., 2014). We conducted qualitative analysis of longitudinal river profiles in order to detect anomalies in the stream profiles and spatial variations of vertical motions.

The geomorphic approach adopted in this work was implemented because these treatments have previously proved to be sensitive to changes in topography by detecting variations in boundary conditions even in regions undergoing low/moderate tectonic deformation rates and high rates of denudation (e.g., Ohmori, 1993; Molin et al., 2004; Dumont et al., 2005; Necea et al., 2005; Pérez-Peña et al., 2009a; Gioia et al., 2014).

## 3.3 Characteristics of Sarawak

### 3.3.1 Geographic and Climatic Setting

Situated in the Sundaland core, Borneo is enveloped by tropical rainforests, mountains and deep valleys that effectively impede and restrain geological and geomorphological research in this region. Sarawak is one of the states belonging to Malaysia and is located on the Borneo Island. The east Malaysian state forms the northwest Borneo segment and borders the Malaysian state of Sabah to the northeast, the Indonesian state of Kalimantan to the south and surrounding the independent state of Brunei (Figure 3.1). Sarawak experiences a tropically hot and extremely humid equatorial climate and can be considered to be uniform at the scale of investigation. Annual mean temperature is of the order of 25° C – 32° C with a relative humidity of ~80 % for much of the year. Annual rainfall in Sarawak varies from 3500 mm $yr^{-1}$ to 4600 mm $yr^{-1}$, spanning 220 days an year with two monsoonal changes (Hua et al., 2013). An estimated 6 km of crust has been removed by erosion from Borneo during the Neogene due to high rates of weathering and erosion (Hall and Nichols, 2002). In terms of sediment yield, rapid removal of material by erosion makes Borneo Mountains comparable to mountain ranges such as the Alps or Himalayas (Hall and Nichols, 2002). A rapid erosional regime is induced with intense chemical weathering in majority of Sarawak.

### 3.3.2 Geology

Geologically, Sarawak can be divided into three distinct regions- west, central and north Sarawak (Tan, 1979). Western Sarawak covers the area to the south of Lupar Line coinciding with the location of the Lupar River. This region consists of shale, sandstones, conglomerates, limestone with volcanic rocks and wide spread igneous rocks of different ages from Carbo-Permian to Miocene. The oldest rocks in west Sarawak are considered to be pre-Upper Carboniferous. Intrusive granitic rocks are confined mainly to this area.

The Rajang and Baram drainage basins predominantly drain the central and north Sarawak regions located at the north and east of the Lupar line (Figure 3.2). Lithologies of both central and north zones are generally composed of sandstones, greywacke, shale, siltstone, clay and minor amounts of limestone and volcanic rocks ranging in age from late Cretaceous to Pliocene (Light et al., 1994, Hutchison, 2005; Siddiqui et al., 2015) (Figure 3.2). A prominent arcuate elevated orogenic zone extends from the north-west to the north-east, through central

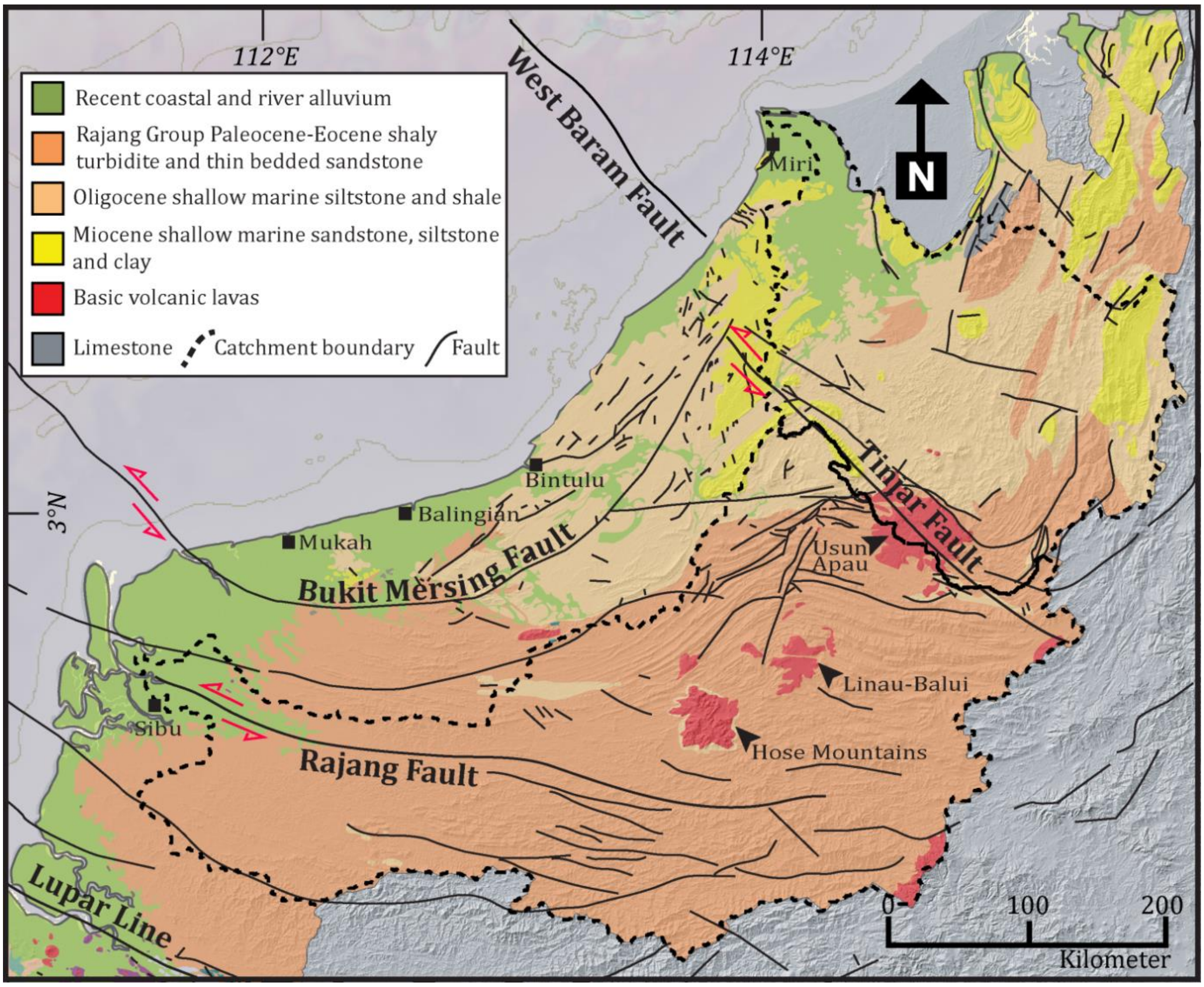


**Figure 3.2.** Simplified geological map of central and north Sarawak. Faults are based on Tate (2001), Simons et al. (2007), and Pubellier and Morley (2014).

Borneo, forming part of the Interior Highlands of Borneo, named as the Sibu Zone in Sarawak (Haile, 1974; Hutchison, 2010) (Figure 3.1). The Interior Highlands of Borneo are mainly composed of the Rajang-Embaluh Group which is a thick succession of strongly deformed Upper Cretaceous to Paleogene deep-water turbidite clastic deposits that crop out in a series of belts from Kalimantan to north Sabah (Tate, 2001; Cullen 2014). The Rajang group, predominantly occurring in the Sarawak part of the Interior Highlands, has been summarized as an Upper Cretaceous-Middle Eocene steeply dipping shaly turbidite with thin sandstone layers (Figure 3.2) (Wolfenden, 1960; Haile, 1962; Hutchison, 2005). These turbidite formations are difficult to date because of the impoverished nature of the microfossil fauna that are often of long-lived 'flysch' foraminifera (Hutchison, 2010). In Sarawak, an angular unconformity separates the Rajang Group from the overlying Oligocene-age shallow marine sediments (Cullen, 2010) (Figure 3.2). The geology of central and north Sarawak is younger than that of west Sarawak and special note must be taken that much of the geologic

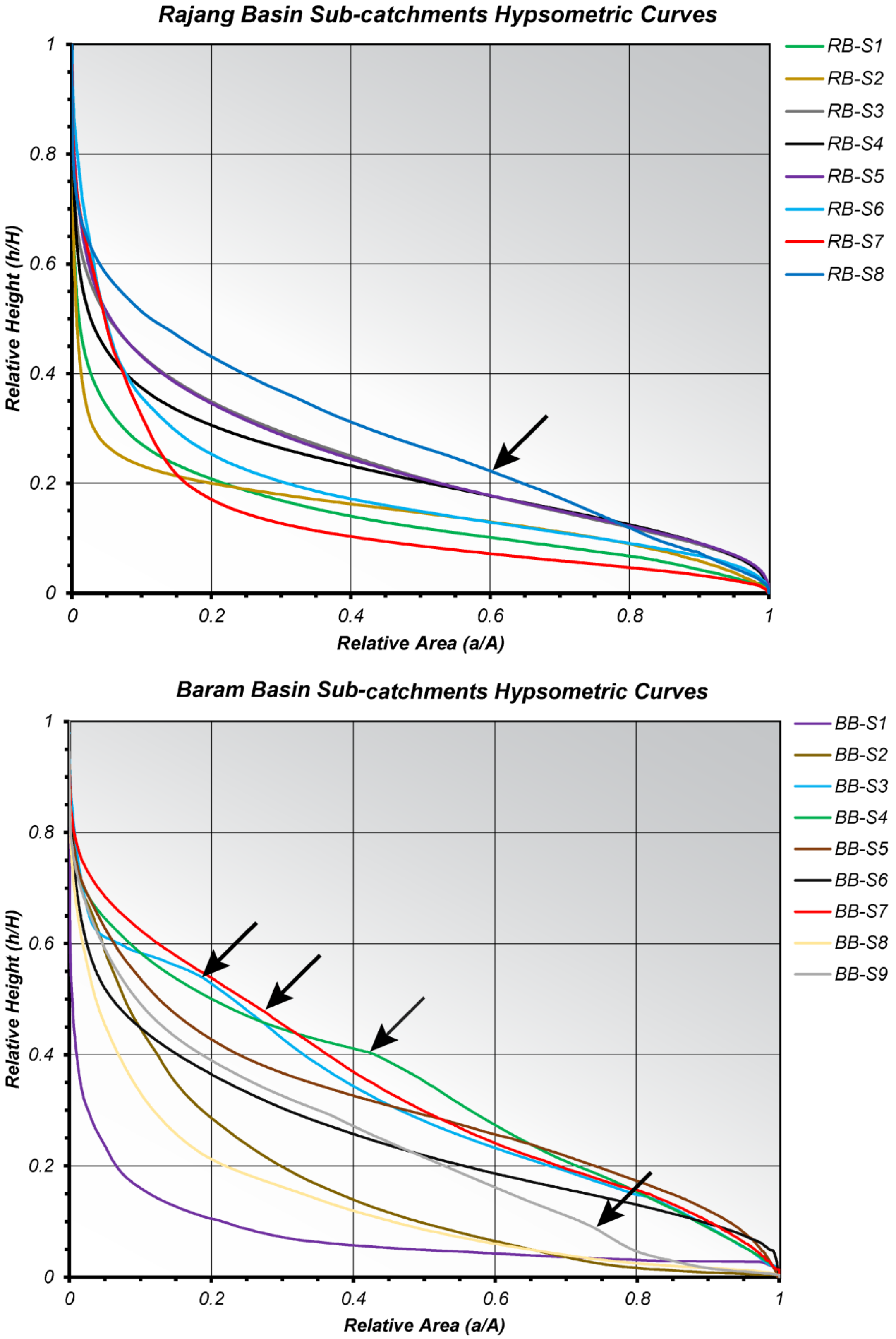


**Figure 3.3.** Hypsometric curves for sub-catchments of the Rajang and Baram drainage basins. The curves have been constructed using parameters derived from 30 m resolution DEMs. Note the black arrows show curves illustrating complex hypsometric curves that do not fit into concave, S-shape or convex shape curves.

mapping of interior Borneo has been carried out only on a reconnaissance scale since access to the interiors is still logistically difficult (Hutchison, 2010). The Miocene sediments in Sarawak consist mainly of shallow marine successions of sandstone, siltstone and clay (Figure 3.2). Faulting and folding are common and appear to have affected all the rocks in the area except the Quaternary.

### 3.3.3 Tectonic and Structural Characteristics

The three zones identified in the geological classification of Sarawak can be applied to the tectonics and structural zonation as well. The Lupar Line, which separates west Sarawak from central and north Sarawak, is interpreted as a strike-slip fault and the line would have probably reactivated several times until Eocene times (Mat-Zin, 1996). Central Sarawak region referred to as Sibu zone by Haile (Haile, 1974), covers the area between Lupar Line and the Bukit Mersing Fault. The Bukit Mersing Fault is interpreted to be of strike-slip nature and active during Eocene to middle Miocene. The fault was reactivated several times and this reactivation along with other movements led to severe deformation of parts of central and north Sarawak (Mat-Zin, 1996). North Sarawak region referred to as Miri zone by Haile (1974) covers the area to the north of the Bukit Mersing Fault.

The central Sarawak terrain is an arcuate fold and thrust belt, commonly referred to as NW Borneo Rajang Group fold-thrust belt, that extends over a distance of >1000 km along strike and a width of over 300 km (Tan, 1979; Williams et al., 1986; Tongkul, 1999). In central and north Sarawak, structural trend lines run in broad curves. The folds are interpreted to be tight, overturned and broken by thrust faults. Episodes of strike-slip faulting followed folding and thrusting of central Sarawak region (Light et al., 1994). The general distribution of folds, normal and strike-slip faults and thrusts may have developed due to periodic northwest to southeast compression or left lateral strike-slip motion along north-northwest trending faults (Tongkul, 1999).

### 3.3.4 Geomorphic Expression

The surficial topography of central Sarawak varies from terrain underlain by recessive shale through zones of linear ridges (interbedded sandstone and shale) to rugged highlands consisting of thick massive sandstones (Light et al., 1994). In the interiors of Sarawak, the landscape is dominated by a wide swath of discontinuous plateaus built of late Cenozoic

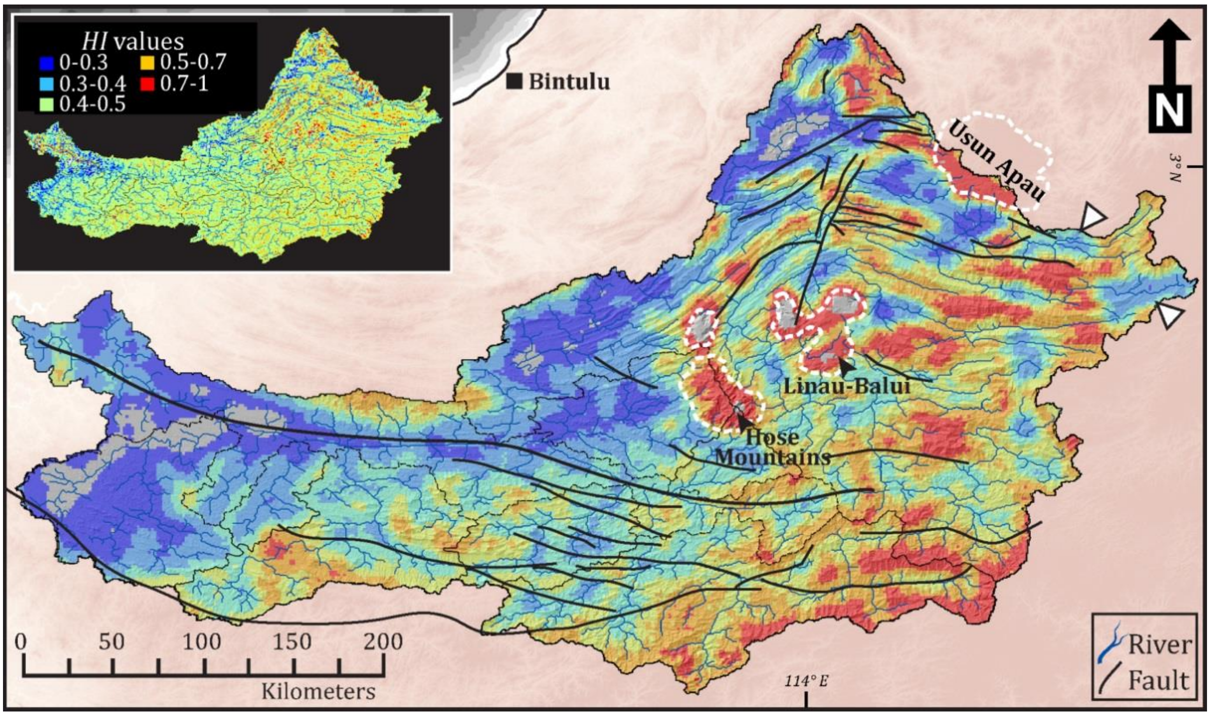


**Figure 3.4.** *Gi** spatial statistics estimation for *HI* values of Rajang Basin. Hotspots are represented by red color and indicates high values of *HI*. Cold spots are represented by blue color and indicates low values of *HI*. Distinct clusters of hotspots and cold spots are visible. Note the coldspots located in the headwaters of the sub-catchment RB-S8 indicated by white arrow heads. Inset figure shows the spatial distribution of *HI* values using an analysis grid of 1 km$^2$, prior to treating it with *Gi** statistics. Note they do not show any pattern pertaining to clusters of high and low values.

volcanic and pyroclastic rocks (Figure 3.2). The Hose Mountain Plateaus (Figure 3.1), consisting of deeply dissected mesa, is about 32 km across rising to 2006 m resting on lower Miocene Nyalau formation equivalent (Kirk, 1957). The Linau-Balui Plateaus covers 290 km$^2$ and rises to 1127 m resting unconformably on folded Belaga formation. It consists of a northern Tableland of 1100 m elevation and a larger southern Tableland of about 820 m elevation. The Usan Apau Plateau is about 906 km$^2$ and rises to 1372 m. The plateau separates a part of the headwaters of the Baram and Rajang rivers (Figure 3.1). The plateau has waterfalls spilling over its rim with plunges of more than 200 m (Hazenbroek and Morshidi, 2001; Cullen et al., 2013). It consists of an eastern Tableland of about 1000 m elevation and a smaller western Tableland of 760 m high (Hutchison, 2005). The mesas have strongly dissected margins with precipitous cliffs and deep marginal embayment. The rivers plunge over the high plateau edges in high cataracts and waterfalls (Hutchison, 2005).

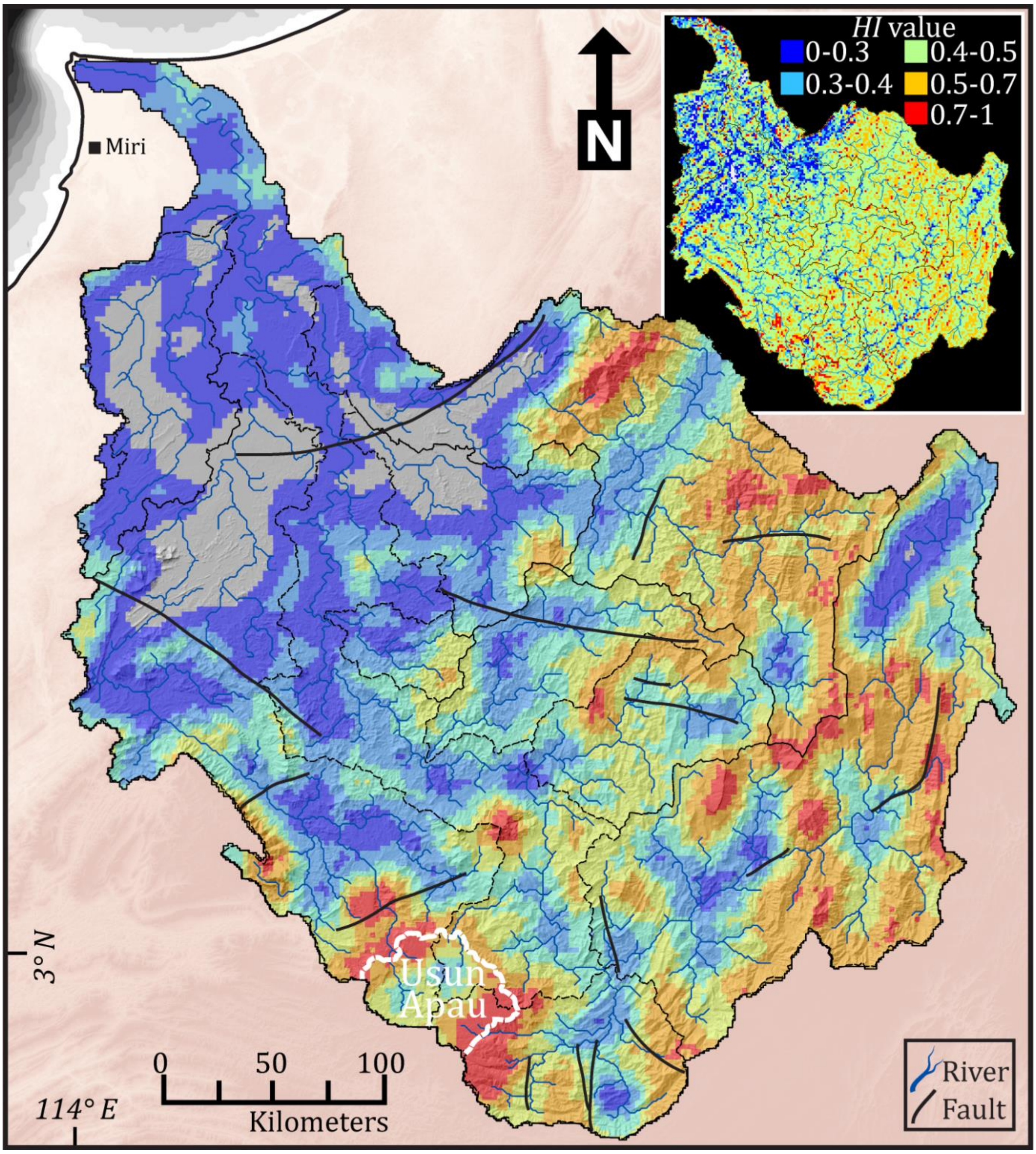


**Figure 3.5.** *Gi** spatial statistics estimation for *HI* values of Baram Basin. Color code for hotspots and coldspots are same as figure 3.4. Distinct clusters of hotspots and cold spots are visible. Note the coldspots located in the headwaters of the sub-catchment RB-S3 and RB-S4 indicated by white arrow heads. Inset figure shows the spatial distribution of *HI* values using an analysis grid of 1 $km^2$, prior to treating it with *Gi** statistics. Note they do not show any pattern pertaining to clusters of high and low values.

### 3.3.5 The Drainage Network

Since Early Miocene, Borneo has experienced a similar ever-wet climate (Hall and Nichols, 2002). Due to the abundant precipitation, Sarawak has an intricate drainage network that rise in the interior ranges and flow through deep gorges and rapids until they reach the coastal plains where they meander before draining into the South China Sea. Here we focus on two river systems of Sarawak that are the most influential on sediment distribution in the South China Sea margin: the Rajang River and the Baram River. The drainage network of these rivers drain entire north and large areas of central Sarawak. The Rajang River flows for ca. 563 km and drains a total area of ca. 50,000 $km^2$ of central Sarawak whereas the Baram River flows for ca. 400 km and drains a total area of ca. 22,100 $km^2$ of north Sarawak. The headwaters of Rajang and Baram basins emerge from the Central Borneo Massif that consists mainly of Cretaceous to Eocene folded and faulted clastic rocks (Wang et al., 2014). These clastics, which make up the ridge topography, are accretionary complexes and forearc basin sediments that were deposited during the Tertiary opening and spreading of the South China Sea (Hutchison, 1996). Hill slopes are steep and flood plains represent very limited areas. Soils in both basins are poorly developed, representing the mineral composition of the parent materials (Scott, 1985). The average monthly sediment discharge rate for the Rajang River basin is 3600 m3/s (Staub, 2000) while the Baram basin delivers at an average, 1445 m3/s of sediments monthly to the South China Sea (Hiscott, 2001).

## 3.4 Materials and Techniques

### 3.4.1 Digital Elevation Models

Most parts of onshore northwest Borneo remain inaccessible due to extensive tropical rainforest and peat swamp cover resulting in poor rock exposures. Complex landscapes are readily accessible and particularly amenable to quantification by the use of Digital Elevation Models (DEMs). The approach adopted by us involves the use of SRTM (Shuttle Radar Topographic Mission) DEM organized within a GIS environment. SRTM DEMs collected by National Aeronautics and Space Administration (NASA) is distributed freely by United States Geological Survey (USGS). The use of this form of digital data is a distinctly pragmatic approach for studying and virtually “visiting” landscapes encompassing large areas where direct physical access may be limited due to hostile terrain and/ or thick vegetation cover. To extract the drainage network, drainage basins and geomorphic analysis, a DEM, in raster format, of 30 m (1-arc second) spatial resolution has been used. SRTM data is acquired using the C and X bands, but only the C band products were used in this study. The DEM was pit/depression filled using Geographic Information Systems software ESRI ArcGIS 10.2

hydrology generic tools in order to remove voids and avoid errors while calculating geomorphic indices. In addition, topographic maps and aerial photographs were used to check the validity of the network and correct anomalous drainage flows.

### 3.4.2 Hypsometric Curves

The first morphometric analysis we used is drainage basin hypsometric curve which is a non-dimensional representation of the hillslope profile and relates the percentage of total relief to the cumulative percentage of area and hypsometric integrals which corresponds to the area below the hypsometric curve (Keller and Pinter, 1996). We employ hypsometric curves and integrals in this study since they are useful geomorphic indicators in terrains experiencing enhanced denudation such as in Borneo as it not only reflects age of landscapes alone, but can indicate erosional processes and patterns along river profiles.

Two types of hypsometric curves can be constructed to represent altitude frequency in drainage basins. The first type of curve has the percentage of sub-catchment elevation relative to the maximum height of the basin as the ordinate, while the abscissa represents the percentage of the sub-catchment area relative to the total basin area (Schumm, 1956). The second type of curve pertains to the hypsometry of the individual sub-catchments where the ordinate represents the sub-catchment elevations normalized against its maximum height, while the abscissa represents the corresponding areas normalized against the sub-catchment total area (Strahler, 1954). Since the second type of curve takes into account the normalized values of individual sub-catchment elevation and area, independent of the master drainage basin, this type of curve is used to extract parameters for comparing sub-catchments of the two studied basins.

### 3.4.3 Spatial Distribution of Hypsometric Integrals

Hypsometric integrals are thought to be affected by basin parameters such as geometry, area and rapid lowering of basin elevations (Lifton and Chase, 1992; Masek et al., 1994; Hurtrez, 1999; Chen et al., 2003; Pérez-Peña et al., 2009a). We computed hypsometric integrals utilizing analysis grid composed of regular squares of area 1 $km^2$ instead of calculating a single value for the entire watershed basin or sub-basin. By calculating hypsometric integral of each square, we obtain a regular distribution of values that is independent of drainage area and basin geometry. The values do not strictly represent a measure of dissection but instead indicate rapid elevation variations within each square (van der Beek and Braun, 1998; Pérez-Peña et al., 2009a). In this study, *HI* values are estimated by means of the following equation (Keller and Pinter, 1996)

$$HI = \frac{Mean\ elevation - Minimum\ elevation}{Maximum\ elevation - Minimum\ elevation}$$

This grid scale was chosen as it takes into account the average dimensions and spacing of the ridges and valleys in the study area, in that the channels follow a hectometric scale and are rarely wider than 1 km. Thus, using a kilometric-scale, we can obtain significant topographic information of the area under investigation (Blanchard et al., 2010). We used this technique due to the large surface area of the studied basins and using small-scale grid cells can aid in the identification of spatial distribution of zones having rapid elevation variations. Using zonal statistics tools, we extracted the maximum, minimum and mean elevation from the DEM for each grid cell.

Because *HI* computation is implemented by us to each individual square rather than calculating a single value for the entire basin following the conventional method, high values can occur together with low values depending if the square is located within a dissected zone of the landscape or a flat zone. If tectonics play an important role in the study area, corresponding *HI* values should follow a general spatial pattern of clusters of high and low values together. To discern whether such patterns exist within the Rajang and Baram basins, we tested the spatial autocorrelation of the data.

### 3.4.4 Spatial Autocorrelation Analysis Moran's *I* and Getis-Ord (*Gi**) Statistics

Spatial autocorrelation measures the degree of sameness of spatially distributed values of a single variable within their neighborhood (Moran, 1950; Cliff and Ord, 1981; Ratcliffe and McCullagh, 1998; Pérez-Peña et al., 2009a; Siddiqui and Soldati, 2014). We used Moran's *I* (Moran, 1950) which is regarded as the best known measure to test for spatial autocorrelation (Pérez-Peña et al., 2009a). The expected Moran's *I* (*E(I))* is calculated assuming a random distribution of the values and is generally very close to 0. The actual Moran's *I* (*I*) values range between -1 and 1, whereby, if *I* is greater than 0, it shows a positive spatial autocorrelation in which similar values of high or low are spatially clustered. On the other hand, if the values are less than 0 or close to -1, it indicates negative spatial autocorrelation showing complete dispersion of values. *Z* score and *p* value are calculated to obtain a confidence level that any pattern of positive of negative association is not just due to chance (Anselin, 1995). Positive *Z* scores indicate clustering, while a negative *Z* score indicates dispersion.

Although used to test spatial autocorrelation, Moran's *I* does not reveal the locations and clusters of high and low values. To determine the concentration of high or low values around a fixed location and to map the corresponding clusters, we used *Gi** statistics. The *Gi** statistics provides specific measures of spatial association by defining a set of neighbors for each location as being those observations that fall within a specified distance (*d*) (Ord and Getis, 1995). The statistics is defined by Ord and Getis (1995) as

$$Gi* = \frac{\sum_j w_{ij}(d)x_j}{\sum_j x_j}$$

where; $w_{ij}(d)$ are the elements of the contiguity matrix for distance (*d*) and $x_j$ is the measured attribute of interest at location *j*.

*Gi** shows the extent to which a location is surrounded by clusters of high values corresponding to hotspots placed together within a specified distance and low values corresponding to coldspots placed together for the variable under consideration (*HI* in this work). This form of statistics has been significantly used globally in various disciplines such as remote sensing, criminology and tectonic geomorphology among others (Pérez-Peña et al., 2009a).

### 3.4.5 Asymmetry Factor

Streams formed under the influence of active tectonics can reflect the direction of deformation. These deformations can be in the form of tectonic tilting caused by flexure or warping of the surface, resulting in longer streams with larger drainage area on one side of the basin as compared to the other; thus creating basin asymmetry. This morphometric index can be defined as (Keller and Pinter, 1996)

$$Af = 100\ (A_r / A_t)$$

where; $A_r$ is the area of a part of a drainage basin on the right of the master stream (looking downstream) and $A_t$ is the total area of the drainage basin. *Af* values close to or equal to 50 signifies no or little tilting indicating a symmetric basin. Values substantially higher or lower than 50 specifies effects of active tectonics or strong lithological control.

Following the methodology defined by Pérez-Peña et al. (2010), we expressed *Af* as the absolute value minus 50 and added an arrow to demonstrate the asymmetry direction.

### 3.4.6 Relative Tectonic Uplift

The evolution and form of landscapes result from the interplay of tectonic and geomorphic processes causing down-wasting due to erosion. Computation of relative tectonic uplift (*U*) for comparing uplift in sub-catchments can be carried out by the means of the following equation proposed by Sinha-Roy (2002),

$$U = hm + (1 - HI)$$

where; *hm* is the mean elevation of the sub-catchment obtained from the elevation covering 50% of the area and normalized against the elevation of the master drainage basin. *hm* can be estimated from the first type of curve discussed in the above hypsometric curve subsection of methods. *HI* is the hypsometric integral.

It has been observed from other studies that hypsometry can be fundamentally affected by tectonic and lithological factors. However, in areas which have experienced a similar climate over long term geological time scales, it has been proved that the influence of lithology on the hypsometric integral persists and holds good only at small scales (~100 $km^2$). Whereas, at larger scales of investigation, as in this work (> ~1000 $km^2$) the integral has proved to be influenced by tectonics (Lifton and Chase, 1992; Pérez-Peña et al., 2009a).

The value generated does not indicate absolute tectonic uplift, but is a measure of relative tectonic uplift in individual sub-catchments of the entire drainage basin. The value of *U* would vary from 0 to 2.

### 3.4.7 Normalized Channel Steepness Index

The normalized channel steepness index ($k_{sn}$) is used to determine tectonically-induced perturbations in channel profiles, as it shows a direct proportionality with uplift rates (Kirby and Whipple, 2001). The slope–area regression has the following form (Flint, 1974)

$$S = k_s A^{-\theta}$$

where $S$ is the local channel slope, $k_s$ is the steepness index, $A$ is the upstream drainage area and $\theta$ is the channel concavity index. A normalized channel steepness index $k_{sn}$ is estimated by normalizing the catchment area of a given reach and using a reference concavity ($\theta_{ref}$) which corresponds to the regional concavity observed in reaches unperturbed by tectonic signals. The above equation can be re-written as

$$S = k_{sn} A^{-(\theta ref)}$$

A reference concavity ($\theta_{ref}$) of 0.45 was used for all channels to facilitate the comparison of our results. $\theta_{ref}$ of 0.45 was chosen as it is within the range commonly perceived in bedrock rivers regardless of rock uplift rates and erosion (Kirby and Whipple, 2001; Wobus et al., 2006).

## 3.5 Results

### 3.5.1 Hypsometric Curve Analysis

The shape of hypsometric curves can be used to infer the erosional stages of catchments and characterize the landscape (Keller and Pinter, 1996). The area below the curve indicates the amount of material remaining after denudational processes has acted on the landscape. Under rapid erosional processes, the left-initial section representing the river-head attains a very sharp gradient since lateral erosion is high in the headward direction; removing material (Ohmori, 1993; Pedrera et al., 2009; Pérez-Peña et al., 2009b).

#### 3.5.1.1 Rajang Sub-catchment Hypsometry

From the hypsometric curves of Rajang basin sub-catchments (Figure 3.3a), it can be observed that sub-catchments RB-S1, RB-S2, RB-S6 and RB-S7 reflect concave curves. RB-S3, RB-S4 and RB-S5 can be seen to be concave at the upstream parts of the curve and attain a gentle convexity at the downstream parts of the curve which can be attributed to the middle-mouth basin zones (Pedrera et al., 2009).  RB-S8 shows an irregular hypsometric curve that cannot be classified into a concave, convex or S-shaped curve and can be said to illustrate a complex hypsometric curve. There are no clear variations in the shape of the curves corresponding to the basins from west to east.

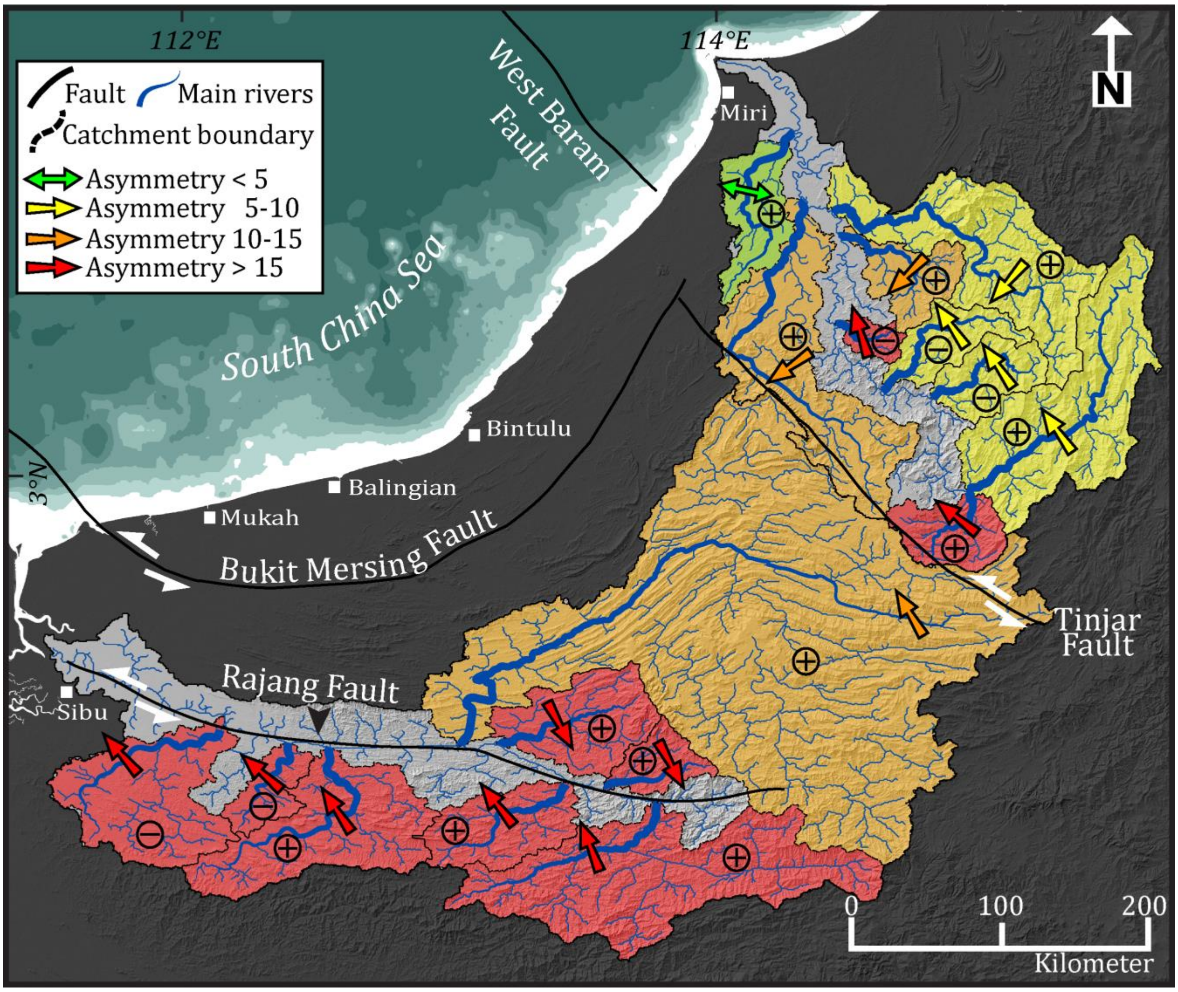


**Figure 3.6.** Widespread basin asymmetry is represented by arrows indicating the asymmetry sense and color indicating the classes. "+"/"-" symbolize relative tectonic uplift value of sub-catchment blocks. Blocks with "+" are relatively uplifted more than blocks having "-" symbol that are subsided or lesser uplifted.

### 3.5.1.2 Baram Sub-catchment Hypsometry

Hypsometric curves of sub-catchments BB-S1, BB-S2 and BB-S8 of Baram basin (Figure 3.3b) show a concave shape. BB-S5 and BB-S6 indicate concavity at the upstream basin zones and show a progressive increase of convexity at the middle-mouth reaches. BB-S3, BB-S4, BB-S7 and BB-S9 show irregular complex hypsometric curves.

## 3.5.2 Spatial Variation in Hypsometry

*HI* was computed using a kilometric-scale analysis grid in order to identify and efficiently record variations in topographic characteristics of the area. The *HI* values of both watershed basins follow a normal distribution with a mean average slightly below 0.5 (Figure 3.4 and 3.5). The *HI* distribution of each square of the analysis grid of Rajang and Baram basin does not show any precise spatially grouped values and varies considerably along adjacent cells due to local contrasts in topography (inset of Figure 3.4 and 3.5).

### 3.5.3 Spatial Statistics

Because *HI* values were distributed spatially with no specific patterns or distinct clusters, spatial autocorrelation statistics is applied to extract clusters of high and low *HI* values. The Moran's scores of both Rajang basin ($I$ = 0.398896; $E(I)$ = -0.000022; $Z$ score = 120.157754; $p$ value = 0.000000) and Baram basin ($I$ = 0.450306; $E(I)$ = -0.000044; $Z$ score = 95.060966; $p$ value = 0.000000) indicate that all the *HI* values are positively correlated and therefore distributed spatially in clusters.

In order to map clusters of high and low *HI* values, the resulting maps were treated with *Gi** spatial statistics. A fixed significance distance of 5 km was used to define the neighbors in the analysis. This threshold distance is sufficient to correlate neighboring grid cells that are affected by deformation in hanging wall and/or foot wall of fault blocks. The results show evident hotspots of high *HI* values and cold spots of low *HI* values (Figure 3.4 and 3.5). In Rajang and Baram basin, hotspots are clustered locally in parts of the Interior Highland fold and thrust belts and cold spots can be observed in the coastal plains. It should be noted that locally cold spots of low *HI* values are found at the headwaters of both basins (Figure 3.4 and 3.5).

### 3.5.4 Basin Asymmetry

In order to supplement the analysis, the area is statistically analyzed through the parameter drainage basin asymmetry (*Af*). The basin asymmetry factor is comprehensively used to identify tectonic tilting transverse to flow at basin level (Figure 3.6). Based on our results we divided the values into four asymmetry classes: class 1 $Af < 5$ showing symmetry; class 2 $Af = 5 – 10$ indicating minor asymmetry; class 3 $Af = 10 – 15$ pertain to moderately asymmetric and class 4 $Af > 15$ exhibit strongly asymmetric drainage basin. The values of *Af* and corresponding classes are tabulated in Table 1.

Of the 8 sub-catchments analyzed in the Rajang basin, sub-catchments RB-S1 – RB-S5 indicates a common northwestwards asymmetry (Figure 3.6). The streams on the left side facing downstream of the master river is shorter compared to the tributaries of the right side facing downstream. Sub-basin RB-S6 and RB-S7 demonstrates a southeastwards asymmetry.

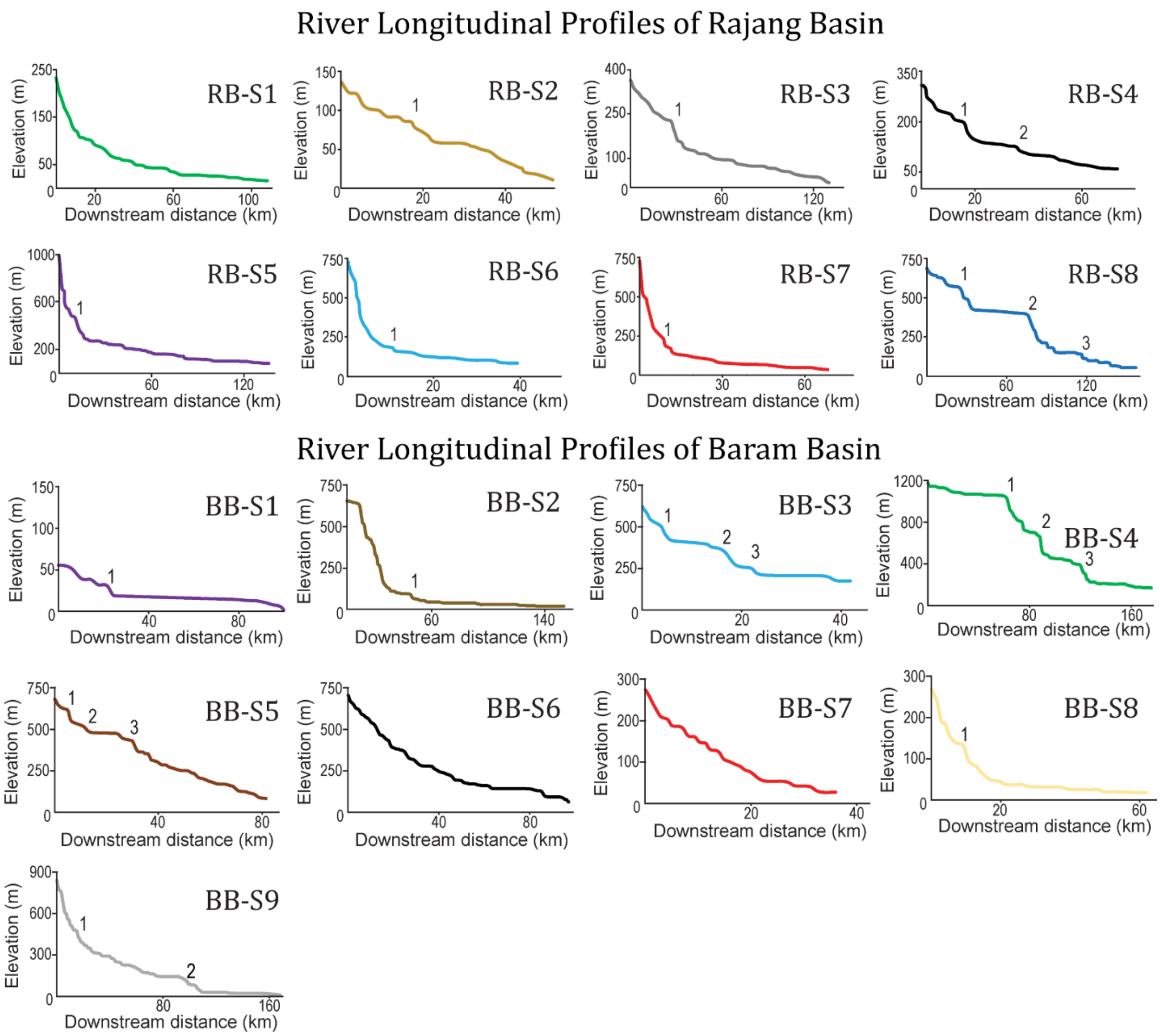


**Figure 3.7.** Longitudinal profiles of trunk streams of all sub-catchments of the Rajang and Baram drainage basin. The numbers represent anomalies pertaining to knick-zones in the channel profile indicating breaks in topography.

Meanwhile RB-S8 shows an asymmetry toward northwest, whereby, the streams on the right side looking downstream of the trunk stream is shorter compared to the streams on the left side facing downstream. Based on the classes, RB-S1 – RB-S7 show the highest values of asymmetry, belonging to the forth class, whereas, RB-S8 belongs to the third class.

In the Baram basin, sub-catchment BB-S1 indicates no significant asymmetry (Figure 3.6). Sub-catchments BB-S2, BB-S8 and BB-S9 show a common southwestwards asymmetry. Sub-basins BB-S3 – BB-S7 indicates a common asymmetry direction toward northwestward whereby the streams on the right side looking downstream of the master river is shorter upon comparison with the tributaries on the left side looking downstream. BB-S1 shows the lowest asymmetric value belonging to class 1 whereas, BB-S4 – BB-S6 and BB-S9 belong to the

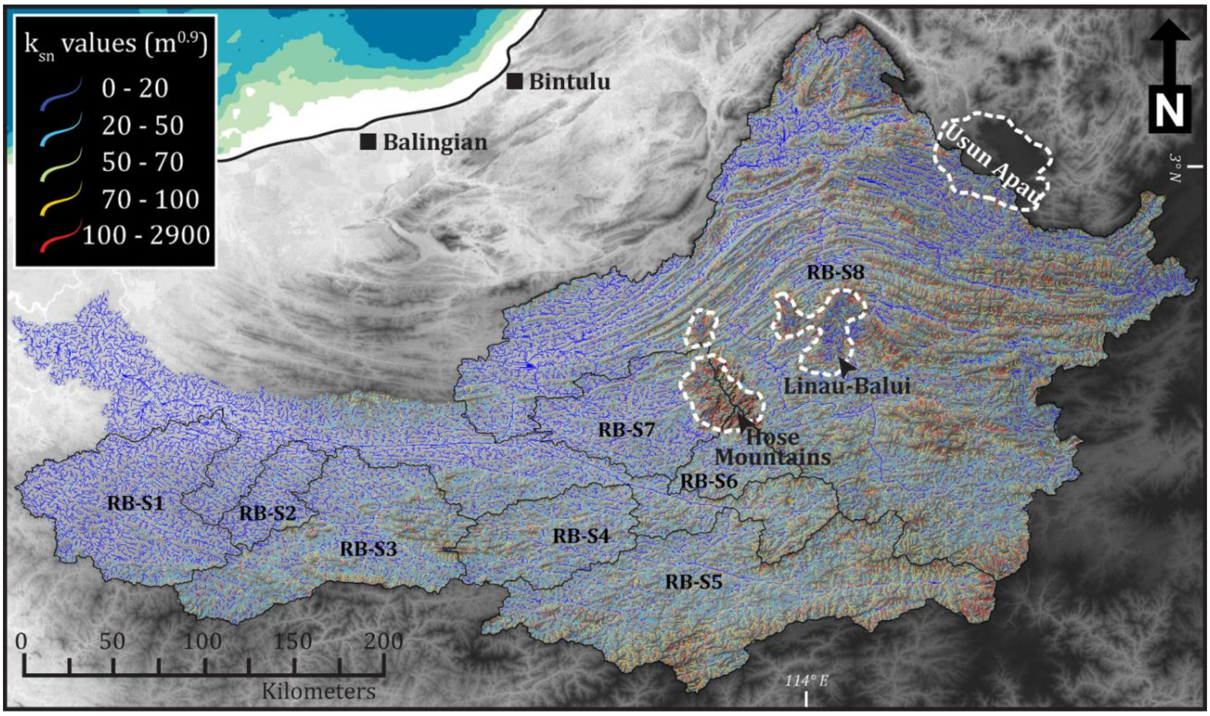


**Figure 3.8.** Map of color coded normalized channel steepness indices ($k_{sn}$) determined for the Rajang basin. Note the low channel steepness in the areas with coldspots in Figure 3.4.

second class. BB-S2 and BB-S8 indicate moderately asymmetric values belong to the third class. BB-S3 and BB-S7 show strong asymmetry with the highest values belonging to the first class.

### 3.5.5 Relative Tectonic Uplift

The relative uplift parameter values of the sub-catchments of Rajang and Baram drainage basins utilizing the empirical relation between uplift (*U*), mean elevation (*hm*) and hypsometric integral (*HI*). The values obtained in this study are shown in Table 1. Uplift (*U*) is a parametric measure of the elevation increase in excess of denudation since the time the present drainage system was formed (Sinha-Roy, 2002). It may be noted that this parametric value does not indicate absolute magnitude of tectonic uplift. As mentioned earlier, hypsometric integrals are influenced by tectonics and lithology of a basin. Indeed, in small basins (~100 km$^2$), lithological controls are most dominant while, the integral has proved to be influenced by tectonics when large scale basins (~ >1000 km$^2$) are studied (Lifton and Chase, 1992; Pérez-Peña et al., 2009a); such as Rajang and Baram Basins. Therefore, the distinction of uplift values observed in the sub-catchments denotes spatial variation in possible tectonically controlled uplift magnitude (Figure 3.6).

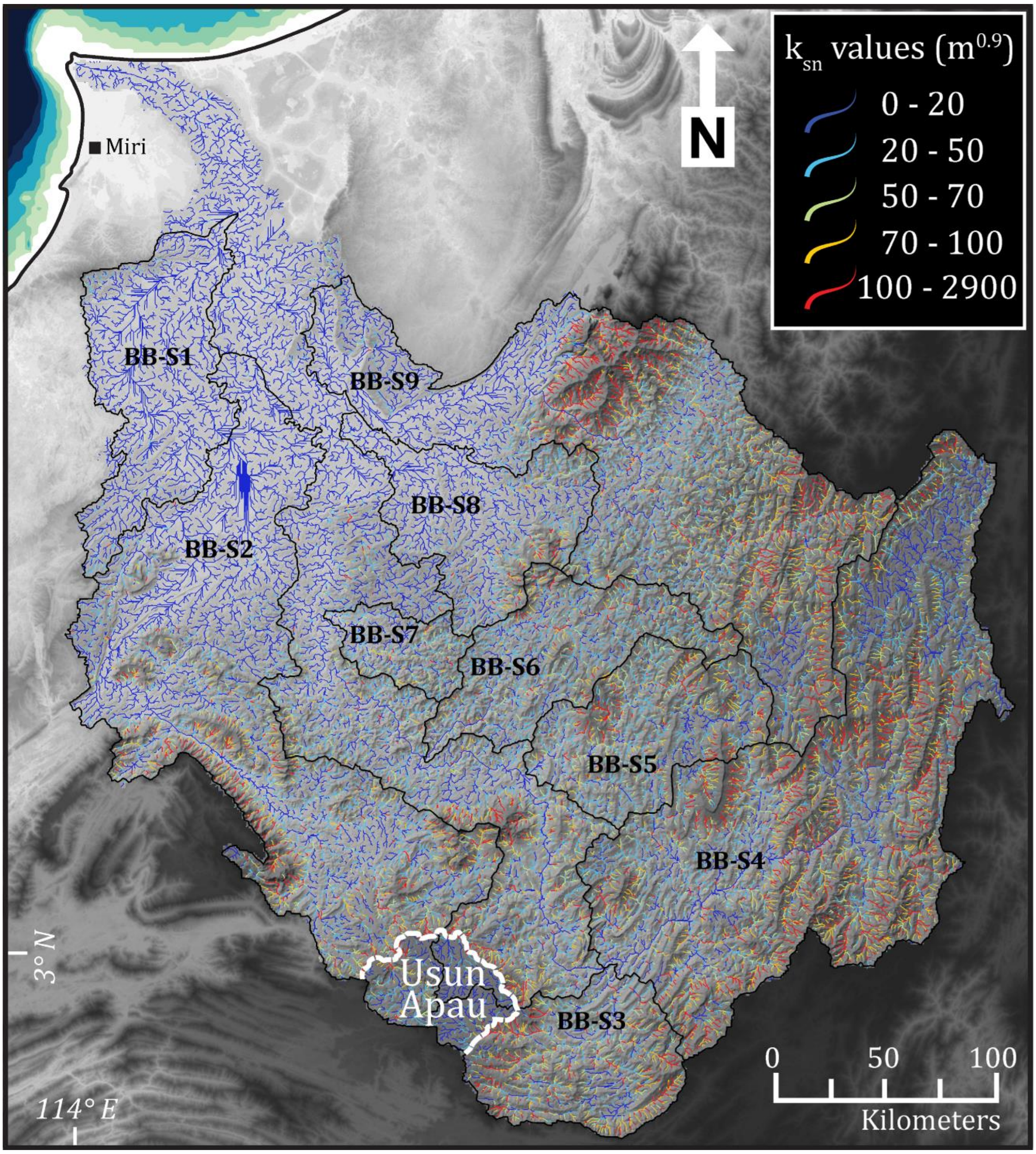


**Figure 3.9.** Map of color coded normalized channel steepness indices ($k_{sn}$) of the Baram basin. Note the low channel steepness in the areas with coldspots in Figure 3.5.

## 3.5.5.1 Rajang Drainage Basin Uplift

Relative tectonic uplift values of sub-catchments of Rajang basin, range from 0.89 – 1 (Table 1) (Figure 3.6). Sub-catchments RB-S1 and RB-S2 show a low range of uplift value (0.89) suggesting either low uplift or slight subsidence. RB-S3 – RB-S8 sub-catchments show the maximum range of *U* value (0.9 – 1) suggesting a strong gradient in values from the upstream


**Figure 3.10.** Field survey photographs for validation of morphometric and morphotectonic analysis. 10A, 10B, 10C and 10D. Waterfalls observed at prominent knick-zones along main channels of RB-S5 (10A) and BB-S3 (10B, C and D). 10E and 10F. Fluvial terraces observed in the RB-S8 indicating surface uplift due to tectonic processes. The basement called Belaga formation, assumed to be of Early Eocene age, is incised by the present day river. Refer to figure 3.1 for location of terraces.

part of the Rajang catchment to the downstream part with RB-S8 showing a value of 1 and adjacent basin RB-S5 also showing a value of 1.

### 3.5.5.2 Baram Drainage Basin Uplift

Sub-catchment tectonic uplift values of Baram basin, range from 0.8 – 1 (Table 1) (Figure 3.6). Sub-catchment BB-S7 shows the lowest uplift value (0.8) which indicates this block is probably a highly subsided block. BB-S5 and BB-S6 sub-catchments show low ranges of uplift values (0.85 – 0.89) which can be interpreted as blocks experiencing either low uplift or mild subsidence. Sub-catchments BB-S1 – BB-S4, BB-S8 and BB-S9 demonstrates the maximum range of uplift value (0.90 – 1).

## 3.5.6 Channel Profile Characteristics

Longitudinal stream profiles of the trunk streams of all sub-catchments of Rajang and Baram drainage basin (Figure 3.7) were extracted. The stream profiles indicate knick-zones into rocks of the Rajang group that mainly consists of shaly turbidites and rocks of the Oligocene and Miocene shallow marine sandstones. It must be noted that only one trunk stream (RB-S7) flow over volcanic rocks of the Hose Mountains. In the Rajang basin, the curves of RB-S1, RB-S6 and RB-S7 exhibit a concave shape which is typical of a reach in equilibrium. Meanwhile, RB-S2 – RB-S5 and RB-S8 show prominent knick-zones with convex segments (Figure 3.7). In the Baram drainage basin BB-S1, BB-S6, BB-S7 shows a concave shape while the other remaining sub-catchments exhibit convexity in their upstream segments.

## 3.5.7 Rajang and Baram Basin Channel Steepness

We calculated normalized channel steepness index for streams of entire Rajang and Baram basin. Color coded maps were prepared for all channels of the catchments as shown in Figures 3.8 and 3.9.

### 3.5.7.1 Rajang Catchment

The 8 sub-catchments of the Rajang basin display varying $k_{sn}$ values (Figure 3.8). Sub-catchments RB-S1 and RB-S2 display the least values of $k_{sn}$ ranging between 10 and 20 $m^{0.9}$ and $k_{sn}$ map does not show any significant spatial disturbances. Generally, lower values of $k_{sn}$ are concentrated within these catchments as they form the mouth of the Rajang drainage basin. RB-S3 and RB-S4 indicate an average $k_{sn}$ of 20 – 45 $m^{0.9}$. Sub-catchments RB-S5 – RB-S8 display higher values of $k_{sn}$ averaging >50 $m^{0.9}$ with RB-S8 illustrating very high values along its headwaters. The Hose Mountains which forms the headwaters of RB-S6 and

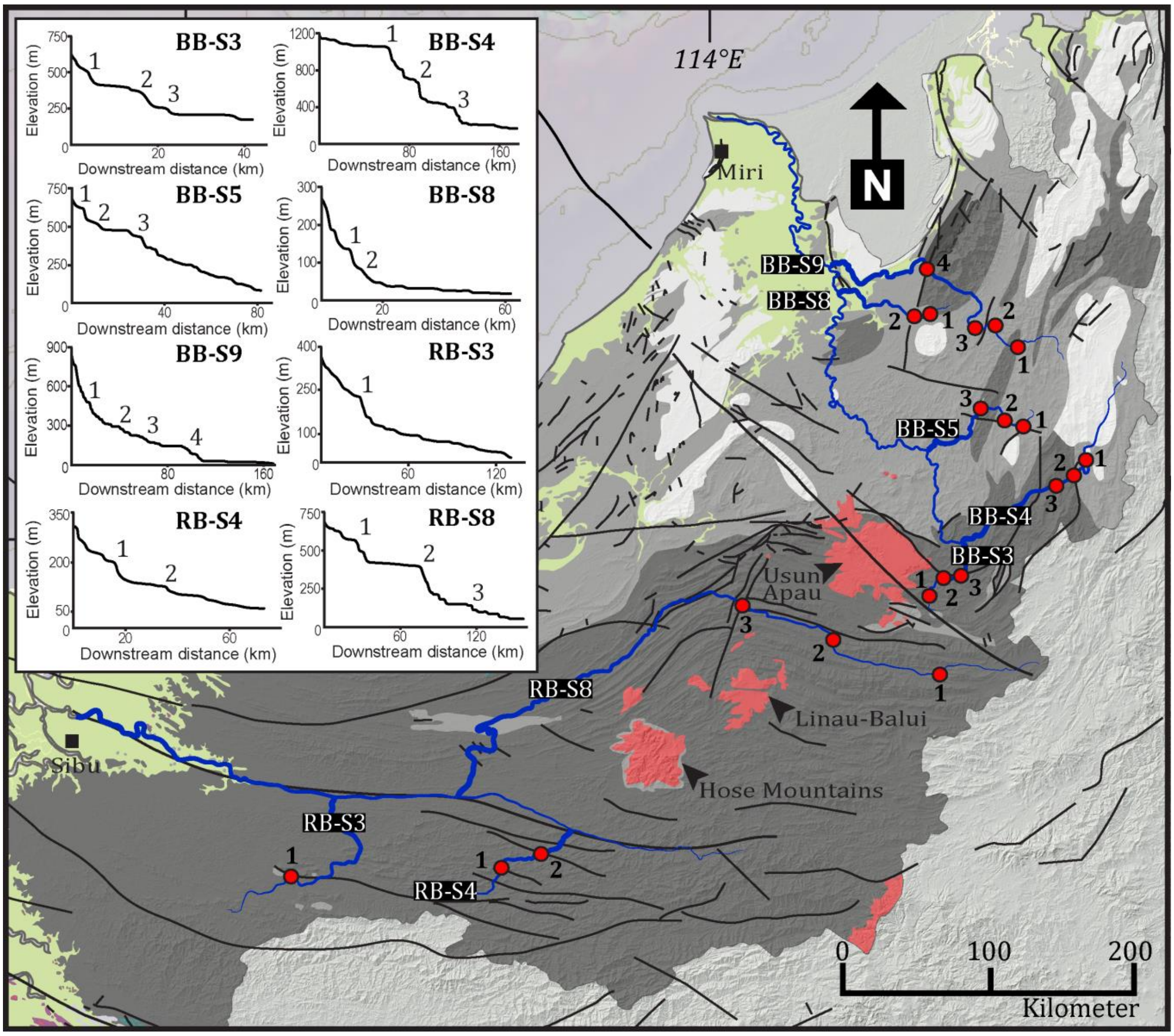


**Figure 3.11.** Longitudinal profiles of master streams of some sub-catchments of the Rajang and Baram drainage basins. The numbers represent anomalies in the channel profiles pertaining to knick-zones. The geological map reveals a few knick-zones related to lithological controls meanwhile most of the knick-zones correspond to faults and some to no apparent lithological and fault controls. Legend for geology is same as figure 3.2.

RB-S7 shows high values of $k_{sn}$. Our results indicated an abrupt shift to high stream steepness values observed in the sub-catchments to the eastern flank of the Rajang basin. Locally, segments of streams in these sub-catchments have very high values >200 $m^{0.9}$ (eg: RB-S8). Fieldwork to accessible parts of these sub-catchments revealed the presence of uplifted fluvial terraces and waterfalls in knick-zones (Figure 3.10). Low $k_{sn}$ values can be observed in the elevated flat volcanic plateaus Linau-Balui and Usun Apau.

### 3.5.7.2 Baram Catchment

Normalized channel steepness index was calculated for all 9 sub-catchments of the Baram basin (Figure 3.9). Distribution of $k_{sn}$ values in sub-catchments BB-S1, BB-S7 and BB-S8

**Table 1.** Hypsometric parameters of sub-catchments of Rajang (RB-S1 – RB-S8) and Baram (BB-S1 – BB-S9) drainage basins

| ***Sub-Catchments*** | ***Asymmetry and class*** | ***Mean Elevation and HI*** | ***Uplift (U)*** |
|---|---|---|---|
| RB-S1 | 28.2 – Class 4 | 0.03, 0.14 | 0.89 |
| RB-S2 | 18.7 – Class 4 | 0.03, 0.14 | 0.89 |
| RB-S3 | 26.4 – Class 4 | 0.13, 0.2 | 0.9 |
| RB-S4 | 23.2 – Class 4 | 0.12, 0.2 | 0.9 |
| RB-S5 | 36.8 – Class 4 | 0.20, 0.2 | 1 |
| RB-S6 | 24.2 – Class 4 | 0.12, 0.2 | 0.9 |
| RB-S7 | 18.7 – Class 4 | 0.09, 0.1 | 0.9 |
| RB-S8 | 12.0 – Class 3 | 0.26, 0.3 | 1 |
| BB-S1 | 0.6 – Class 1 | 0.01, 0.08 | 0.93 |
| BB-S2 | 12.6 – Class 3 | 0.07, 0.17 | 0. 9 |
| BB-S3 | 25.7 – Class 4 | 0.20, 0.3 | 0.9 |
| BB-S4 | 9.3 – Class 2 | 0.34, 0.3 | 1 |
| BB-S5 | 7.4 – Class 2 | 0.19, 0.3 | 0.89 |
| BB-S6 | 8.6 – Class 2 | 0.15, 0.3 | 0.85 |
| BB-S7 | 17.0 – Class 4 | 0.10, 0.3 | 0.8 |
| BB-S8 | 11.5 – Class 3 | 0.04, 0.1 | 0.9 |
| BB-S9 | 9.8 – Class 2 | 0.21, 0.2 | 1 |

showed an average value of <25 $m^{0.9}$ with the lowest values displayed on relatively flat floodplain topography. Sub-catchments BB-S2 – BB-S6 and BB-S9 displayed high values of $k_{sn}$ averaging > 55 $m^{0.9}$. Anomalously high channel steepness and gradients were noticed especially in streams of sub-catchments BB-S3, BB-S4 and BB-S9 with segments showing values > 300 $m^{0.9}$ (Figure 3.9). Knick-points corresponding to a number of waterfalls and/or faults were observed along the segments showing high values (Figure 3.10).

## 3.5.8 Field Campaigns

The field surveys revealed deeply incised V-shaped valleys, knick-points corresponding to waterfalls and terraced boulder to gravel sized fluvial deposits unconformably overlain above the incised basement rocks (Figure 3.10).

## 3.6 Insights on Active Tectonics through Morphotectonic Investigation of Sarawak

We investigated the occurrence of recent tectonic phasess and their associated deformation, and resulting geomorphic expressions with regard to surface processes and landscape response to forcings in northern Borneo. Our analysis focused on quantitative and qualitative geomorphic assessment of two of the largest drainage basins located in Sarawak: Rajang and Baram Drainage Basins (Figure 3.1). The results of tectono-geomorphic assessment show that north Borneo experiences neotectonic perturbations and the response to changes in boundary conditions have shaped the current topography.

Borneo a part of the Sundaland core of South East Asia, is described to have a weak thin lithosphere, eminently receptive to plate boundary forces with unusually high rates of erosion (Hall, 2011). Hypsometric curves of basins have the capability of elucidating erosional patterns and processes along channel profiles and denudation stages of catchments. Following the classification of basins and subsequent curves proposed by Strahler (1952), indeed majority of the curves of sub-catchments in both Rajang and Baram drainage basins reflect concave curves which shows a highly denuded topography. Strahler (1952) suggested a convex shape for a basin in its youthful stage, S-shaped curves for a mature stage and concave curves for a subdued peneplain stage. However, based on the size of the studied basins in Sarawak, it could be noticed from the headwaters to the downstream segments of each sub-catchment, there are areas with different degrees of dissection (Figure 3.1). Hence, depending on the ratio of eroded to under-eroded terrain and the magnitude of erosional wave propagating from the downstream to upstream segments of the landscape, the shape of the curve could only show either a S-shape or concave shape with a high left-initial section representing the river-head. This has been proved by studies conducted on large basins (> 1000 $km^2$; each extending from the headwaters in the mountain to the river mouth at the coast) located in areas experiencing rapid erosion and their results showed the curves were concave or S-shaped but never convex despite having very young mountain ranges (Plio-Pleistocene) (Ohmori, 1993; Pérez-Peña, 2009a).This could suggest that the curve would maintain these shapes even if subject to tectonic uplift in the upstream reaches of the Rajang and Baram drainage basins. Therefore, our results could confirm the findings of previous studies (Ohmori, 1993; Pérez-Peña, 2009a) that mountain ranges formed under and progressively being subjected to strong erosion, and experiencing recent or active uplift in the headwaters, could demonstrate concave or S-shaped curves. It should be noted that the Rajang basin sub-catchment RB-S8 and Baram basin sub-catchments BB-S3, BB-S4, BB-S7 and BB-S9 show curves which do not fit into either S-shape or concave shapes (Figure 3.3a and 3.3b). Since the shape of the curve has the ability to describe lateral erosion in the headward direction, it can be positively correlated to rejuvenation processes, piracy events or differential uplift (Pedrera et al., 2009). These processes would increase erosion in the basin and the curves relating to such processes would show an irregular shape or would show a "complex hypsometric curve" as suggested by Giaconia et al. (2012). Visual examination of DEMs of the sub-catchments of Rajang and Baram basins with complex hypsometric curves shows a number of streams that have incised into strike-line ridges creating gorges, leaving possible windgaps. The drainage network of BB-S3 and BB-S4 (Figure 3.1) shows streams with orthogonal convergence points which are another diagnostic feature of capture events pertaining to the elbow of capture. Recently, numerical models have provided insights regarding capture processes, large scale basin evolution and quantifying differential uplift rates (Giachetta et al., 2015). However, at present only this form of visual observation using remotely sensed data can be used in areas such as Borneo because as mentioned by previous workers (Hutchison, 2010; Cullen et al., 2013), fieldwork to these zones of Rajang and Baram basin to retrieve initial input parameters for numerical models remains difficult.

Theoretically, rejuvenation and stream capture events may occur in rivers experiencing disequilibrium due to changes in boundary conditions. A river in disequilibrium would then reflect this perturbation as breaks in topography described as knick-points or knick-zones. These topographic breaks are caused by parameters such as: (a) tectonic forcing resulting in differential uplift, (b) bedrock erodibility variation and/or (c) drop in base-level due to high frequency sea level variations during the Quaternary (Strahler, 1957). Hence, the presence of knick-zones in the longitudinal stream profile can be used as reliable indicators of the stream network and the landscape adjusting to changes in boundary conditions (Giletycz et al., 2015). Channel profiles of Rajang and Baram basin exhibit various knick-zones of which the prominent knick-zones are noticed in RB-S3, RB-S4, RB-S8, BB-S3, BB-S4, BB-S5, BB-S8 and BB-S9 (Figure 3.11). Of these sub-catchments, RB-S8, BB-S3, BB-S4 and BB-S9 showed complex hypsometric curves (Figure 3.3a and 3.3b). Field campaigns (where accessible) to some of the knick-zones revealed waterfalls in sub-catchment RB-S8 of Rajang basin with topographic breaks of more than 50 m elevation and sub-catchment BB-S3 of Baram basin with breaks of more than 100 m elevation (Figure 3.7 and 3.10).The basins RB-

S8, BB-S3 and BB-S4 are located more than 200 km from the coast and the outlet is at a minimum elevation of ca. 100 – 200 m. Moreover, since the knick-zones are located at various altitudes in adjacent watersheds, there is no correlation with any narrow elevation range throughout the drainage network. Due to this, we discard the possibility that the knick-zones in these basins may have formed because of a fall in base-level due to sea level fluctuations. It can be observed that only few of the knick-zones correspond to lithological contrasts while many of the knick-zones are located along known faults identified from previous works and some knick-zones without any apparent lithologic or fault control (Figure 3.11). Therefore, most of the prominent knick-zones may be related to changes in tectonic boundary conditions which cause an increase of convexity in the channel profile toward the upstream direction. These interpretations are consistent with our results of *HI* hotspots shown in these zones (Figure 3.4 and 3.5). Distinctly high values of *HI* can be seen in sub-catchments RB-S8, BB-S3, BB-S4 and BB-S9. The hotspots indicate anomalous variations in elevations and since they do not represent a measure of incision; they do not show lithological contrasts. This is evident from the hotspot map of Baram basin (Figure 3.5) where prominent hotspots are clustered only along the rims of the Usun Apau volcanic plateau. The $k_{sn}$ maps prepared in this study are congruent with all locations of hotspots illustrating high channel steepness and gradients with RB-S8, BB-S3, BB-S4 and BB-S9 showing very high $k_{sn}$ values along their reaches (Figure 3.8 and 3.9). Considering that both basins share consistently similar climatic conditions, it may be deduced from the maps that the hotspots corresponding to high *HI* values and high $k_{sn}$ values demonstrate less eroded landscapes affected by relatively high uplift rate. It should be noted that the volcanic plateaus, Usun Apau and Linau-Balui and the Hose Mountains show hotspots of rapid elevation variation along with high $k_{sn}$ values recorded along the rims of the plateaus and the hillslopes of the Hose Mountains. These results are due to the fact that elevation is bound to rapidly vary with respect to their surrounding due to the highly resistant volcanic rocks that demonstrate slower incision rates as compared to sedimentary rocks and subsequently maintain high channel steepness along the rims and hillsopes. Due to these factors, the volcanic plateaus and Hose Mountains are discarded from the interpretations of hotspot and $k_{sn}$ maps.

Onshore Sarawak, the main tectonic structures observable is compressional fold and thrusts producing crustal shortening. During the Miocene, compression was dominantly ubiquitous in large parts of offshore and onshore Sarawak resulting in folding. Central and southern

Sabah experienced this phase of tectonism with a relatively stronger magnitude resulting in strong folding associated with basement uplifts and wrench faulting (Darman and Sidi, 2000). This compressional regime may be linked to the first convergence of Australia and Southeast Asia at ca. 23 Ma. The oblique convergence may have been accommodated by both strike-slip faulting and crustal shortening. During the Upper Neogene, a transgressive phase of rising sea-levels occurred in Sarawak (Hutchison, 2005). Sarawak and north Sabah experienced a phase of deformation triggered by trough basement uplifts and wrench faulting during the Pliocene (Darman and Damit, 2003). Evidences of folding and thrusting as a result of these tectonic stages have been observed offshore by previous works (Cullen, 2010; Menier et al., 2014). In regions experiencing high erosion rates such as Borneo, geomorphic expressions of recent tectonic perturbations can be removed rather rapidly and uplift rates of tectonic phases should be very high in order to maintain a young topography that retain evidences of recent tectonic signals. Thus, results from our analysis could reveal that folding related to crustal shortening has occurred in the recent past (< 5 Ma) and could still be prevalent in the onshore fold and thrust belts of the Rajang Group Interior Highlands of Sarawak. Recent studies have confirmed that most of the high terrains in the islands of Southeast Asia are young (< 10 Ma) and mountain ranges have grown in the past 5 Ma (Molnar and Cronin, 2015), further confirming the results obtained by us.

The active crustal shortening could possibly reactivate old dislocations related to wrench faults and parallel thrusts within both the basins; especially noticed in sub-catchments RB-S3, RB-S4 and RB-S5 showing anomalies in their stream profile at locations of known wrench systems (Figure 3.7 and 3.11). The shortening of the crust could be accommodated along the Tinjar Fault which is across-strike of the fold and thrust belts. This could explain the recent GPS data confirming a relative movement of the fault at a rate of 3 mm yr-1 (Simons et al., 2007). Reactivation of faults due to tectonics and their resulting surficial uplift can be recorded by rivers in the form of fluvial terraces in these deposits are vestiges of former floodplains that get exposed due to uplift. Conventional field work to accessible parts of the studied drainage basins revealed waterfalls (Figure 3.10) and terraced boulder to gravel sized fluvial deposits unconformably overlain above the basement rocks. High $k_{sn}$ values are observed along the stream with the uplifted fluvial terraces and waterfalls (Figure 3.4 and 3.8). Active folding could also have created an orographic effect throughout Sarawak and along with a rise in sea-level during Upper Neogene, could have promoted headward incision. This wave of incision could have led to piracy events as a result of disequilibrium induced in the channel network due to uplift and exacerbated precipitation rates, explaining the complex hypsometric curves in some sub-catchments located in the interior highlands. Although Borneo has experienced a similar climate since Early Miocene (Hall and Nichols, 2002), it is more than likely the island must have undergone an increase in precipitation rates with amplified erosion and consequent escalated sediment flux due to orographic effect since 5 Ma.

It is noteworthy that the hotspot maps are able to highlight coldspots of low *HI* in the upper reaches of RB-S8, BB-S3, BB-S4 and BB-S9, located at high elevations with low corresponding $k_{sn}$ values (Figure 3.4, 3.5, 3.8 and 3.9). These coldspots may represent relict planation surfaces characterized by low local relief which have been uplifted to their present day elevations. The planation surface in BB-S4 consists of Miocene shallow marine deposits (Figure 3.2 and 3.5) at a present-day elevation of ~1100 m. Assuming these surfaces could have been graded to sea-level during Miocene, uplift of this terrain since 5 Ma, to its present-day elevation, would yield an average minimum uplift rate of 0.22 mm $y^{-1}$ which is consistent with the long-term (2 Ma) base-level lowering estimated by Farrant et al. (1995) from limestone caves and surrounding shale formations in Mulu, Sarawak which showed results of 0.19 +0.03/ -0.04 mm $y^{-1}$ and 0.23 mm $y^{-1}$ respectively. However, for an estimation of uniform uplift since 5 Ma would require one to envisage a subdued topography, graded to sea-level, for approximately 300 km from the coast taking into account the distance of this surface from the present-day shoreline. Since Borneo is considered to have fully emerged during this time and the palaeo-shoreline was approximately where it is in the present-day (Hall, 2002), peneplanation is highly unlikely as there was intense folding and uplift during end of Miocene times (Darman and Damit, 2003) and adjacent peaks within the same basin have elevations of ~2400 m (Figure 3.1) which would require higher uplift rates than 0.22 mm $y^{-1}$. Moreover, very low rates of denudation and incision would have to be presumed if uniform uplift since 5 Ma has to be presumed. Thus, in order to sustain high elevations despite rapid denudation rates, it could be possible that Borneo has experienced a phase of high uplift rate since 5 Ma or multi-phased rapid uplift with pulses of fast and slow uplift. This phase of uplift could be related to the proto-South China Sea slab-breakoff which could induce a large-scale uplift of the entire fold–thrust belts of the Interior Highlands of Borneo (Sapin et al., 2013). Another explanation that seems plausible for the origin of these surfaces could be that they represent isolated remnants of capture zones which are unable to balance high uplift rates due to their streams being captured by adjacent basins, explaining the complex hypsometric curves of RB-S8, BB-S3, BB-S4 and BB-S9. This seems to be a reasonable justification considering the preserved flat topography of these surfaces indicating low incision and erosion rates. In the light of the above explanations, in either case, it is possible to consider the present-day drainage network of Sarawak could be reasonably young (< 5 Ma) and could have undergone a reorganization of the drainage network at a local scale. These sub-basins also show higher relative uplift values as compared to their adjacent basins (Figure 3.6 and Table 1). The basins also indicate asymmetry (Figure 3.6) related to large-scale northward tilting indicative of a tectonic control. The direction of deformation indicated by basin asymmetry can be positively correlated with the direction of folding in the Rajang Group fold and thrust belts.

## 3.7 Conclusion

Tectono-geomorphic investigation of Rajang and Baram drainage basins of northern Borneo elucidate that these basins have been subjected to an increase of tectonic activity since 5 Ma resulting in rapid uplift of terrain which probably continues up to the present. The topography is still evolving while adjusting to disequilibrium caused by changes in tectonic boundary conditions and active folding within the Rajang Group thrust belt would still be persistent.

The results from hypsometric curves suggest that given the size of the basins consisting of areas with different degrees of dissection, the terrain indicates a young and transitory stage that is subject to rapid denudation. The distribution of hotspots relating to high *HI* values obtained through spatial autocorrelation statistical techniques indicate hotspots concentrated in the Rajang fold and thrust belt which occupies some of the sub-catchments of both basins. The hotspots indicate rapid elevation drops and show relatively less eroded topography subject to uplift despite being within locations of uniform lithology and climate. High $k_{sn}$ values pertaining to steep channel gradients can be observed along the zones showing hotspots of high *HI*. Coldspots of low *HI* values and very low channel steepness situated at high elevations in the headwaters of some sub-catchments with complex hypsometric curves are observed in both basins. These surfaces could be related to remnants of paleosurfaces that were not eroded due to high uplift rates or remnants of capture processes owing to rapid tectonic uplift and exacerbated orographic precipitation since 5 Ma. All the sub-catchments with the exception of one (located in the coastal plain regions of Baram basin) show asymmetry with majority indicating northward tilting demonstrating the direction of deformation and it can be correlated with the direction of the arcuate fold and thrust belt.

Relative uplift values of sub-catchments demonstrate relatively elevated blocks and highly to mildly subsided or relatively lesser elevated blocks related to fault movements which may have been reactivated due to active folding. Prominent knick-zones along channel profiles of both basins with no apparent lithological controls show neotectonic activity and a transient stage of topographic adjustment as a result of folding.

Bearing in mind the rapid erosion rates affecting Borneo, these expressions of tectonics could be maintained only if the topography is considerably young and are diagnostic of regions undergoing rapid tectonic uplift. Borneo could have experienced high rates of tectonic uplift since 5 Ma or multi-phased uplift with periods of fast and slow uplift or subsidence in between, and because of high denudation rates, this deceleration would allow the topography to adjust swiftly to a transient stage.

# *Chapter* 4

# Drainage Basin and Topographic Analysis of a Tropical Landscape: Insights into Surface and Tectonic Processes in northern Borneo

Mathew, M., Menier, D., Siddiqui, N., Ramkumar, M., Santosh, M., Kumar, S., Hassaan, M., 2016. *Journal of Asian Earth Sciences* 124, 14-27.

## *Contents*

## 4.1 Abstract

We investigated the recent landscape development of Borneo through geomorphic analysis of two large drainage basins (Rajang and Baram basins). The extraction of morphometric parameters utilizing digital terrain data in a GIS environment, focusing on hydrography (stream length-gradient index, ratio of valley floor width to valley height, and transverse topographic symmetry factor) and topography (local relief, and relief anomaly), was carried out in order to elucidate processes governing drainage and landscape evolution. Anomalously high and low values of stream length-gradient indices of main tributary streams associated with faults and multiple knick-points along the channel profiles are linked to deformation events. The development of deeply incised V-shaped valleys show enhanced incision capability of streams in response to steepening of hillslope gradients following tectonic inputs. Deflection of streams and probable dynamic reorganization of the drainage system through stream capture processes as feedbacks to tectonic uplift and orographic effect are observed. Local relief and relief anomaly maps highlight the presence of preserved elevation-accordant relict portions of landscapes characterized by low amplitude relief, nested between ridgelines in regions of complex folding. Our results reveal dynamic geomorphic adjustment of the landscape due to perturbations in tectonic and climatic boundary conditions. The implication is that the landscape of north Borneo experienced a tectonic phase of rapid uplift after 5 Ma and undergoes active folding of the Rajang Group thrust belts in the present-day. Active shortening combined with high rates of denudation in Sarawak, demonstrates transience emphasized by the drainage system attempting to adjust to tectonic and climatic forcing.

Keywords–geomorphology; tectonic uplift; Borneo; relief; landscape evolution

## 4.2 Introduction

Internal tectonic processes deform the lithosphere while external climate forcing shapes the surface topography. Any perturbation caused by these processes will shift a landscape from its state of dynamic equilibrium to a state of disequilibrium. The landscape would then tend toward a stable steady-state from its state of disequilibrium; while passing through a stage of transience (Montgomery and Foufoula-Georgiou, 1993; Willgoose, 1994; Giletycz et al., 2015). Signatures of disequilibrium and transience can be observed in the morphometric properties of river networks that drain the surfaces of these landscapes (Medwedeff, 1990; Keller and Pinter, 1996; Mueller and Talling, 1997; Delcaillau et al., 1998; Tate et al., 2001; Delcaillau, 2004; Willett et al., 2006; Burbank and Anderson, 2011).

Geomorphometry facilitates quantitative assessment of temporal stages of landscape development by numerical representation of topographic parameters (Pike, 1995; Pike, 2000; Jordan, 2003; Rasemann et al., 2004). Morphometry helps analyze and characterize topography by examining the corresponding drainage basins, stream networks and/ or mountain fronts. Drainage basins represent dynamic systems that may retain records of formation and progression since most tectono-geomorphic processes occur within its confines (Romshoo et al., 2012; Dar et al., 2014). Thus, landscape development is the result of the evolution of individual drainage basins of which it is composed (Singh, 1980; Dar et al., 2014).

Geomorphic characteristics of drainage basins and stream networks can be effectively interpreted using remotely sensed digital topographic data (such as Digital Elevation Models/DEMs) and Geographical Information System (GIS) software (Slaymaker, 2001; Hajam et al., 2013; Waikar and Nilawar, 2014). These tools enable rapid, precise and reproducible analysis of fluvial channels and characterization of landscapes (e.g.,Tarboton et al., 1991; Dietrich et al., 1993; Montgomery and Foufoula-Georgiou, 1993; Moglen and Bras, 1995; Tucker, 1996; Sklar and Dietrich, 1998; Weissel and Seidl, 1998; Snyder et al., 2000). The use of this form of digital data is a distinctly pragmatic approach for studying and virtually “visiting” landscapes encompassing large areas where direct physical access may be limited due to hostile terrain and/ or thick vegetation cover.

The tectonically complex Borneo island is the third largest island in the World, shared by Malaysia (Sarawak and Sabah), Indonesia (Kalimantan) and Brunei. It is enveloped by vastly inaccessible tropical rainforests, mountains and deep valleys that effectively impede and restrain geological and geomorphological research in this region.

Here we demonstrate the response of the tropical landscape of north Borneo to perturbations in tectonic boundary conditions utilizing variables extracted from remotely sensed data on

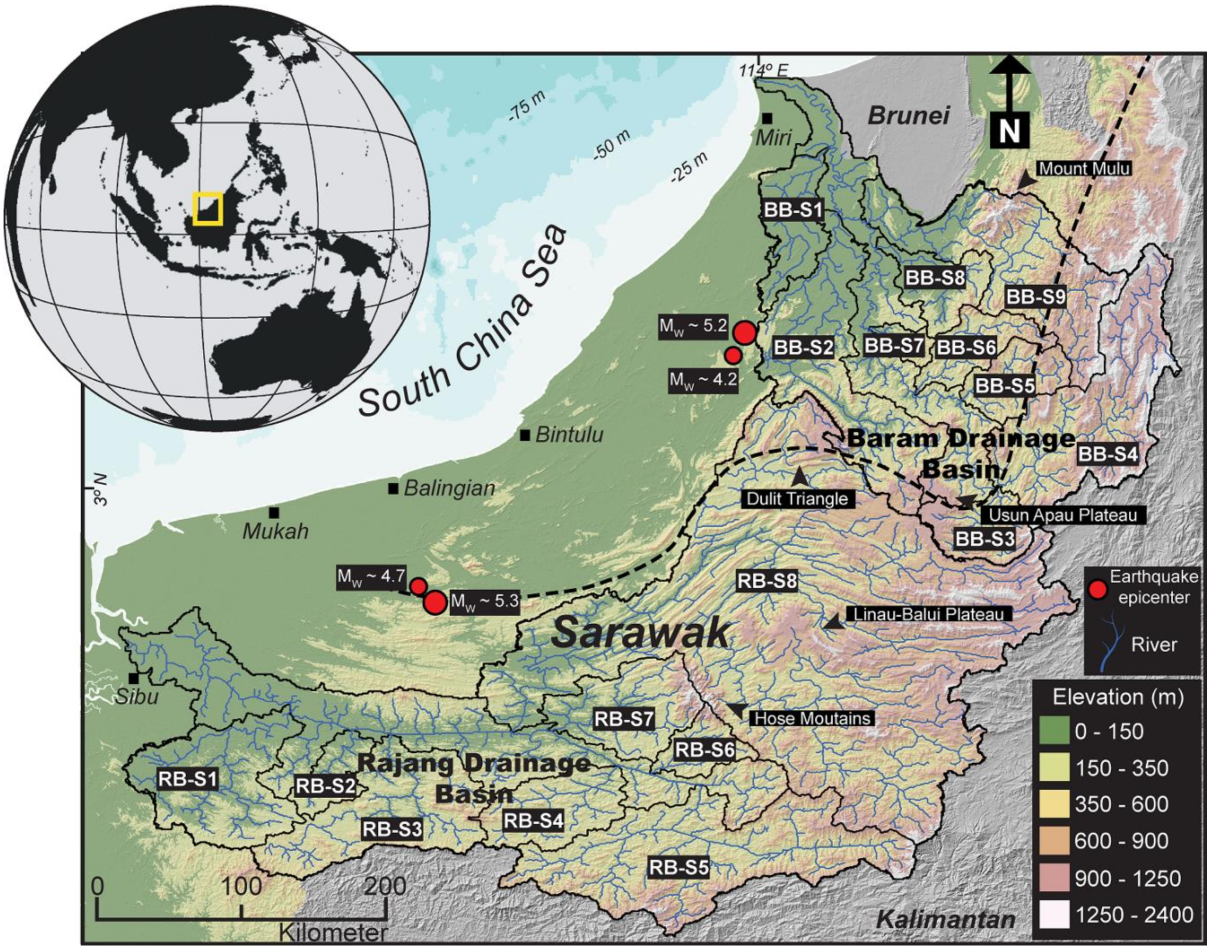


**Figure 4.1.** Shaded relief model of the study location of Rajang and Baram drainage basins of north Borneo. The sub-catchments of both basins are demarcated by black solid lines and numbered accordingly; RB-S1 – RB-S8 for sub-basins of Rajang basin and BB-S1 – BB-S9 for sub-basins of Baram basin. The drainage network is shown in blue solid lines for reference. Red circles denote locations of recent seismicity and their corresponding magnitude on the Richter scale is indicated. Also shown are some of the important highlands and tablelands of north Borneo. Black dashed-line marks the approximate northern limit of the Interior Highlands of Borneo.

two large drainage basins: Rajang and Baram Basin (Figure 4.1) and organized within a GIS environment. These basins are located in the central and northern parts of Sarawak. Sarawak is considered to experience an intra-plate setting since at least Late Miocene and in this region studies pertaining to neotectonic activity and the consequent geomorphic response to forcings are scarce and inadequately constrained.

## 4.3 Geological and Geomorphic Setting

Borneo along with Malay Peninsula, Sumatra, Java and Palawan is part of Sundaland that forms the continental promontory of the Eurasian plate in SE Asia (Hall and Morley, 2004). Borneo, a part of the Sundaland core of South East Asia, is reported to have a weak thin lithosphere, and unusually high rates of denudation as a result of plate boundary forces, and remarkably rapid vertical movements along with gravity-driven movements of the upper crust (Hall, 2011). Borneo is a region of large swathes of rugged terrain with highlands and mountain ranges exceeding elevations of 2000 m in the interior of the island north of the equator covering ~450 000 $km^2$ in area (Hall and Nichols, 2002).

The studied basins: Rajang and Baram Basins are the two major catchment systems of northern Borneo and are located in the central and northern parts of Sarawak.

### 4.3.1 General Geography and Climate of Sarawak

Sarawak is one of the states belonging to Malaysia and is located on the island of Borneo. It forms the northwest segment of Borneo and borders the Malaysian state of Sabah to the northeast, the Indonesian state of Kalimantan to the south and surrounding the independent state of Brunei. Sarawak experiences an equatorial climate that is tropically hot and extremely humid and can be considered to be uniform at the scale of investigation. Annual mean temperature is of the order of 25° C – 32° C with a relative humidity of ~80 % for much of the year. Annual rainfall in Sarawak varies from 3500 mm $yr^{-1}$ to 4600 mm $yr^{-1}$, spanning 220 days an year with two monsoonal changes (Hua et al., 2013). A rapid erosional regime is induced with intense chemical weathering in majority of Sarawak.

### 4.3.2 Tectonics and Geology

Structurally and geologically, Sarawak is divided into three distinct regions- west, central and north Sarawak (Tan, 1979). Both central and north zones are composed of sandstones, greywacke, shale, siltstone, clay (Hutchison, 2005; Siddiqui et al., 2015) and minor amounts of limestone and volcanic rocks ranging in age from late Cretaceous to Pliocene (Light et al., 1994) (Figure 4.2). In central and north Sarawak, structural trend lines run in broad curves. The central Sarawak terrain, covering the area between Lupar Line and the Bukit Mersing Line, is an arcuate fold and thrust belt called the Rajang Group Fold-Thrust belts that extends over a distance of < 1000 km along strike and a width of over 300 km (Tan, 1979; Williams et al., 1986) (Figures 4.3A and 4.3B). This zone composed of the orogenic belt, named as Sibu Zone in Sarawak (Haile, 1974), forms the Sarawak part of the Interior Highlands of Borneo (Figure 4.1), and has been summarized as an Upper Cretaceous-Middle Eocene steeply dipping shaly turbidite with thin sandstone layers (Figure 4.2) (Wolfenden, 1960;

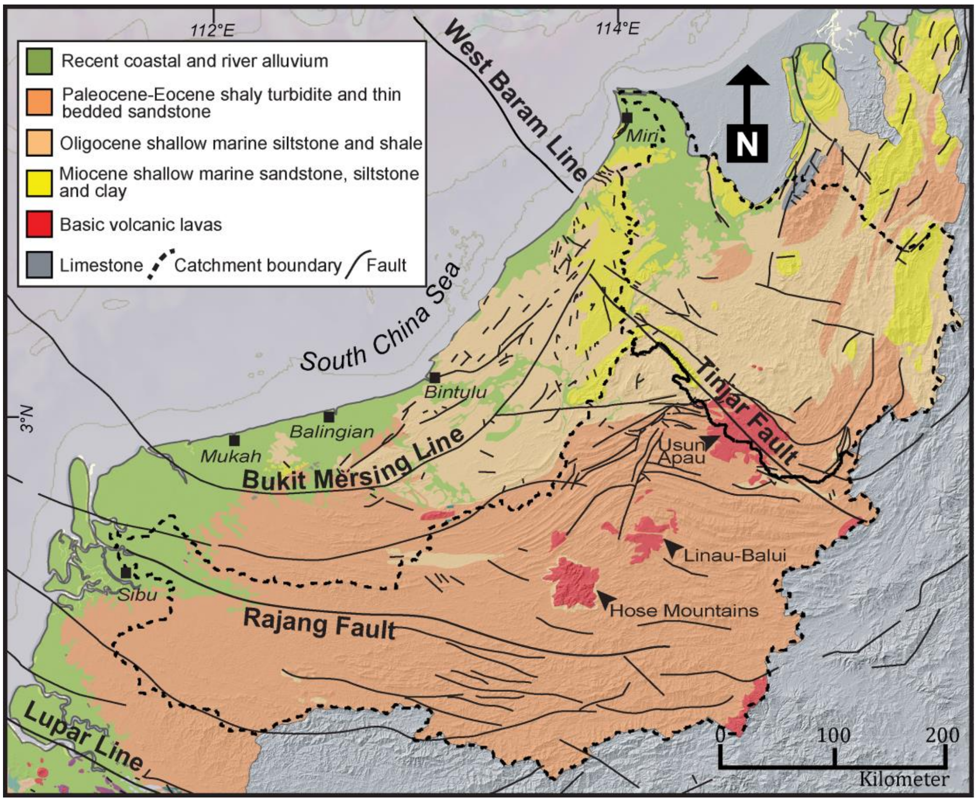


**Figure 4.2.** Simplified geological map of central and north Sarawak, Borneo along with major faults and structural lines. Apart from the minor amounts of volcanic and pyroclastic rocks of the Hose Mountains and, Linau-Balui and Usan Apau plateaus, the dominant lithologies are relatively lesser resistant rocks. Rajang and Baram basin boundaries are shown by black dashed-lines.

Haile, 1962; Hutchison, 2010). The uplift of the Sibu Zone is interpreted to have occurred at the end of the Eocene, an event referred to as the 'Sarawak Orogeny' (Hutchison, 2005, 2010). The folds of this belt are described to be tight, overturned and broken by thrust faults (Tongkul 1997; Honza et al. 2000; Cullen, 2010) with at least one major thrust fault in between the formations within the Group. Episodes of strike-slip faulting followed folding and thrusting of central Sarawak region (Light et al., 1994).

The present-day (1960 – 2014) seismicity of north Borneo shows a sparse distribution in Sarawak with average magnitude of >4.5 (Figure 4.1) occurring along the Rajang and Tinjar Faults.

## 4.3.3 Geomorphological Characteristics

The surficial topography of central Sarawak varies from terrain underlain by recessive shale through zones of linear ridges (interbedded sandstone and shale) to rugged highlands

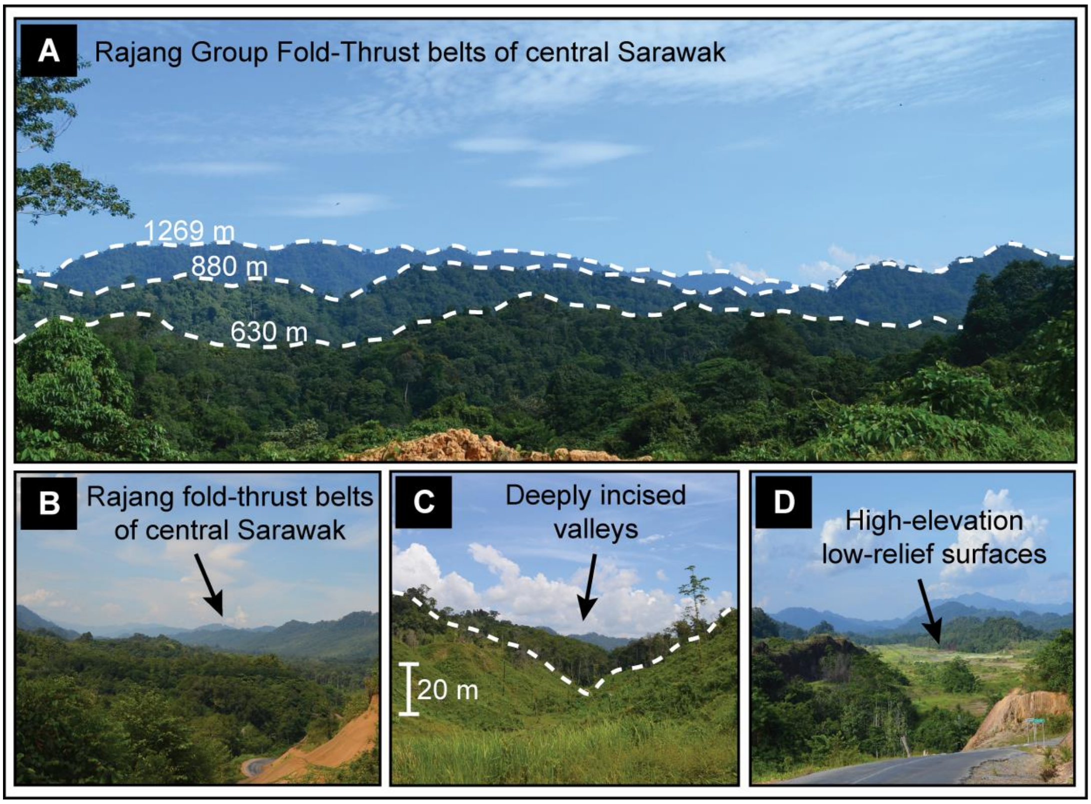


**Figure 4.3.** (A) and (B) Panoramic photographs (field photographs) of a part of the strongly folded and thrusted mountain belts of central Sarawak. These < 1000 km long and > 300 km wide arcuate orogens are results of periodic compression and/or strike-slip motion. (C) Deeply incised valleys are prominent features visible in the fold and thrust belts of north Borneo. (D) Planation low relief surfaces perched at high-elevation topography. Refer to figure 4.8 and 4.11 for locations.

consisting of thick massive sandstones (Light et al., 1994; Siddiqui et al., 2015). In the interior of Sarawak, the landscape is dominated by a wide swath of discontinuous plateaus built of late Cenozoic volcanic and pyroclastic rocks (Figures 4.1 and 4.2). The Hose Mountain Plateau, consisting of deeply dissected mesa, is about 32 km across rising to 2006 m rests on lower Miocene Nyalau Formation equivalent (Kirk, 1957). The Linau–Balui Plateaus covers 290 $km^2$ and rises to 1127 m resting unconformably on folded Belaga Formation. It consists of a northern Tableland of 1100 m elevation and a larger southern Tableland of about 820 m elevation. The Usun Apau Plateau is about 906 $km^2$ with small dissected volcanos that rise to 1372 m (Cullen, 2013). The plateau along with the Tinjar Fault separates the Baram and Rajang basins (Figure 4.1). The plateau has high cataracts and waterfalls spilling over its rim with plunges of more than 200 m (Hazenbroek and Morshidi, 2001; Cullen et al., 2013).It consists of an eastern Tableland of approximately 1000 m elevation and a smaller western Tableland of 760 m high (Hutchison, 2005). The Usun Apau and Linau–Balui volcanic plateaus and Hose Mountains are considered to be younger than 4 Ma (Cullen et al., 2013).

## 4.4 Data and Techniques

### 4.4.1 Digital Terrain Data

In this work, we conducted topographic and morphometric analysis on SRTM (Shuttle Radar Topography Mission) DEMs having spatial resolution of 1 arc-second (~30 m) that were seamlessly mosaicked together. The DEM mosaic was then pre-processed in a GIS environment by filling sinks in the DEM through interpolation from surrounding pixels following algorithms defined by Jenson and Domingue (1988) to obtain a homogenous dataset without data-void pixels. Where necessary, we used a combination of Landsat OLI PAN (Operational Land Imager Panchromatic) and multi spectral images for computing ratio of valley floor width to valley height. For narrow valleys of width < 60 m, the DEM resolution was found to be insufficient to extract precise valley width measurements. In those situations, we pan-sharpened the Landsat OLI PAN images and then the multi spectral images were fused using Subtractive Resolution Merge (SRM) to increase both spatial and spectral resolution. The SRM fusion method was chosen as it adopts a strategy to combine two images by image segmentation associated with a RGB color analysis to group pixels into like categories (Canavosio-Zuzelski, 2011).To highlight topographic features, the images were treated with linear contrast enhancement. Then, the images were draped over the pre-processed DEMs and co-registered to produce datasets of RMSE (Root Mean Square Error) below 0.3.

In addition, field surveys were organized to locations which could be logistically accessed in order to detect evidences of anomalies and establish a direct control on geomorphological features to complement the quantitative analysis. The objective of the field work was to examine the possible impact of local lithology on channel morphology and verify knick-points and sedimentary stratigraphic records (terraced fluvial deposits) of tectonic uplift.

### 4.4.2 Quantitative Morphometric Analysis

We conducted morphometric analysis of Rajang and Baram Basins by obtaining geomorphic indices at sub-basin scale for allowing meaningful inferences of landscape development in large areas of heterogeneous geomorphic and structural characteristics. The quantitative

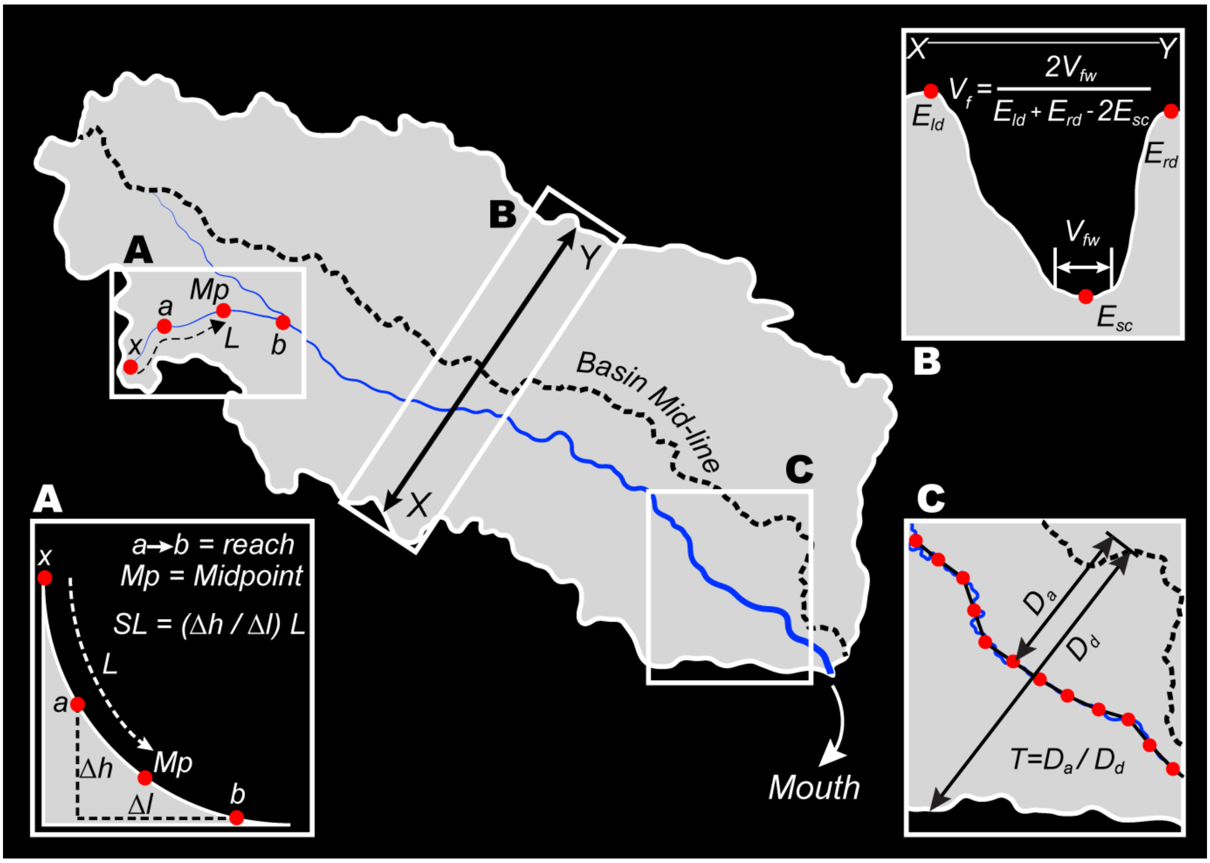


**Figure 4.4.** Conceptual figure of an idealistic drainage basin indicating parameters and corresponding variables used for quantitative morphometric analysis conducted in this study. (A) Stream length-gradient index ($SL$), (B) Ratio of valley floor width to valley height ($V_f$) and (C) Transverse topographic symmetry factor ($T$).

indices used are: stream length-gradient index ($SL$), ratio of valley floor width to valley height ($V_f$) and transverse topographic symmetry factor ($T$) (Figure 4.4). These indices have previously proved to successfully demonstrate anomalies in fluvial systems and valley morphology produced by local changes in tectonic uplift and erosional processes (Malik and Mohanty, 2007; El Hamdouni et al., 2008; John and Rajendran, 2008; Pedrera et al., 2009; Dehbozorgi et al., 2010; Font et al., 2010; Toudeshki and Arian, 2011; Dar et al., 2014) . We supplemented our analysis by constructing local relief and relief anomaly maps to highlight topographic features and substantiate the interpretations.

### 4.4.2.1 Stream Length–Gradient Index ($SL$)

$SL$ index was defined by Hack (1973) as;

$$SL = \left(\frac{\Delta h}{\Delta l}\right) L$$

where; $\Delta h/\Delta l$ is the channel gradient or slope of the reach and $\Delta h$ represents the variation of altitude for a channel of the reach with respect to $\Delta l$ that signifies the length of the reach. $L$ is the total horizontal channel length from the divide to the midpoint of the channel reach upstream for which the index is being calculated (Figure 4.4).

$SL$ index is effective in characterizing stream gradient conditions and to analyze the relation between probable recent tectonic activity that alters slope gradient, topography, rock resistance to erosion and length of streams (Keller and Pinter, 1996; Zhang et al., 2011; Dar et al., 2014). It can be roughly related to stream power as erosional capability of rivers adjust to rock resistance while trying to achieve dynamic equilibrium. This implies that $SL$ values would be high where rivers and streams flow over active uplifts. Conversely, lesser $SL$ values indicate low tectonic activity and when rivers flow over less-resistant and softer underlying rocks.

### 4.4.2.2 Ratio of Valley Floor Width to Valley Height ($V_f$)

This index is described as the ratio of the width of the valley floor to its average height (Bull and McFadden, 1977; Bull, 1978). The index is defined as;

$$V_f = \frac{2V_{fw}}{E_{ld} + E_{rd} - 2E_{sc}}$$

where; $V_{fw}$ is the width of the valley floor, $E_{ld}$ and $E_{rd}$ are the elevations of the left and right valley divides respectively and $E_{sc}$ is the average elevation of the valley floor (Figure 4.4).

Comparison of the valley floor width to its mean height yields an index ($V_f$) that measures rapid down cutting and lateral erosion into adjacent hillslopes by rivers. $V_f$ was established to discriminate between valleys with a wide floor relative to the height of the valley walls with a "U" shape to narrow, steep valleys with a "V" shape (El Hamdouni et al., 2008). Deep, V-shaped valleys are expressions of regions subjected to active uplift resulting in linear and rapid stream incision and consequently narrowing the valley floor. Low values of $V_f$(<0.5) are associated with higher rates of uplift and incision. In addition, flat-floored, wide valleys with high $V_f$(>0.8) values indicate the attainment of base-level of erosion and tectonic quiescence (Keller and Pinter, 1996).

### 4.4.2.3 Transverse Topographic Symmetry Factor (*T*)

$T$ factor evaluates the amount of asymmetry of a stream within a catchment and the variation of this asymmetry in different segments of the valley. The midline of drainage basin would be the location of a stream that is symmetrically placed with regard to the drainage divide (Verrios et al., 2004). It is calculated using the larger axis of the basin, extending from the outlet to the most distal point in the headwater (Khavari et al., 2009). For a perfect symmetric basin, value of $T$ will be 0. As the asymmetry increases, $T$ would increase toward 1, assuming that shift of stream channels is an indication of possible surface tilting resulting in variation of slope polarity and the influence of bedrock on stream migration is negligible. $T$ is defined as;

$$T = \frac{D_a}{D_d}$$

where; $D_a$ is the distance from the midline of the drainage basin to the midline of the active meander belt and $D_d$ is the distance from the basin midline to the basin divide (Keller and Pinter, 1996) (Figure 4.4).

### 4.4.3 Topographic Analysis

We investigated the topographic features of Rajang and Baram basins in terms of relief values, focusing on the spatial variation in maximum, mean and minimum elevations. These were extracted to produce a local relief map that provided an overview of the topographic heterogeneity and river incision patterns. In order to track these fluctuations, and to record abrupt changes in relief pattern at short distances, an analysis grid composed of cells having an area of 1 $km^2$ was adopted. We computed the local relief map as the residual relief between maximum topography which is the peak elevations displaying surfaces without fluvial dissection and the minimum topography corresponding to the general pattern of valley bottom elevations.

To further evidence anomalies in topographic relief, we constructed a relief anomaly map to highlight surfaces displaying low local relief at high elevations. It represents elevations normalized with respect to the local relief. Relief anomaly is defined by Scotti (Scotti et al., 2014) as;

$$A_r = \frac{H_{mean}}{R_l}$$

where; $H_{mean}$ is the mean elevation of the raw topography and $R_l$ is the local relief.

## 4.5 Results

### 4.5.1 $SL$ Index

In order to assess landscape development in north Borneo, we performed stream length-gradient index ($SL$) on the main tributary streams of Rajang and Baram drainage basins. The results are illustrated in figures 4.5 and 4.6. The index was determined from a DEM in GIS environment considering $SL$ points a value of 1 km as a calculation for fixing interval. The interval distance was chosen to provide a high resolution analysis of the predominantly long main streams of both basins. Our results highlighted peculiarities in the stream longitudinal profiles with an array of knick-zones indicating topographic breaks (Figures 4.5 and 4.6). Anomalously high and low values of $SL$ are observed in both basins. Anomalously high values of $SL$ are observed especially in streams of RB-S5 and RB-S8 with gradient index peaks of 1500 and above. Similarly in Baram basin, $SL$ gradient index peaks exhibit very high values of over 6000 in BB-S4 and above 1000 in streams of BB-S2, BB-S3, BB-S5, BB-6 and BB-S9. The detected anomalies of values coincide with highly deformed terrain having topographic steps (Figure 4.7).

### 4.5.2 $V_f$ Index

The $V_f$ index was computed for all the channels of main valleys crossing mountain fronts of both the studied drainage basins. As valleys upstream from the mountain front tend to be narrow, the index was determined at a set distance of ̴1 km upstream from the mountain front. We determined the heights of valleys from a DEM and where the resolution was insufficient for accurate measurement of valley floor width (width < 60 m), we extracted measurements from high resolution satellite imagery (Refer to data and techniques).In order to decrease the margin of error, verification of values extracted from DEMs and satellite images was done by comparing with field measurements obtained using handheld GPS to accessible parts of the studied basins. $V_f$ values for the basins are shown in figures 4.8 and 4.9. $V_f$ values are relatively low for most of the valleys with the exemption of low-lying subdued topographic

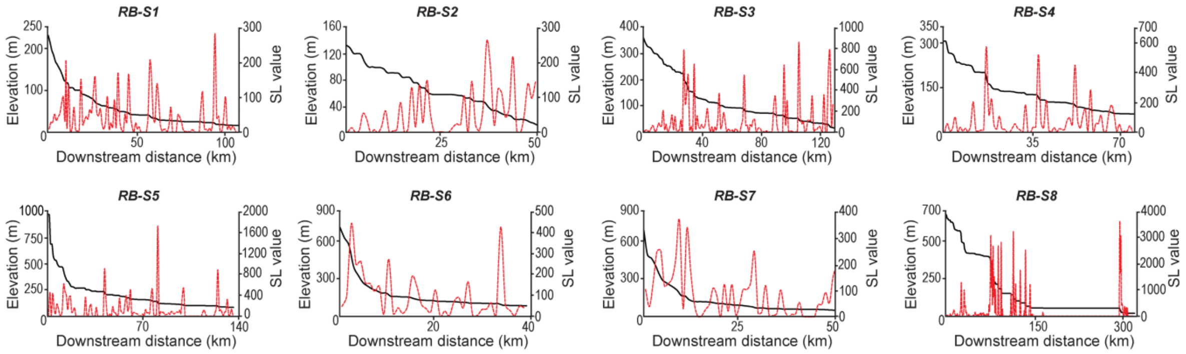


**Figure 4.5.** $SL$ anomaly profiles and corresponding stream longitudinal profiles of main tributary streams of the Rajang drainage basin. Note high peaks of $SL$ values corresponding to topographic breaks and/or knick-points are often recorded in the middle and lower reaches of all but two profiles (RB-S6 and RB-S7) while the upper reaches show no prominent peaks. Also note the flat upstream segment of RB-S8. Main tributary streams used for analysis and knick-point locations are shown in figure 4.11.

zones in both basins. The values computed by us elucidate V-shaped deep linear incised valleys in structurally complex zones. It can be noted that remarkably low values are observed in valleys of sub-catchments RB-S5 and RB-S8 and likewise in sub-catchments BB-S3, BB-S4 and BB-S9 of Rajang and Baram drainage basins respectively.

### 4.5.3 *T* Factor

Transverse topographic symmetry factor was determined for all the main tributary streams of both Rajang and Baram basins in order to identify variations in symmetry of the streams. We calculated $T$ at an appropriate fixed interval of 10 km. From our results, noticeable stream deflection and migration can be observed (Figure 4.10).

### 4.5.4 Relief Anomaly

Values of mean local relief of both basins are low despite the highly deformed, folded and thrusted terrain of north Borneo (Figure 4.11). The highest values of (between 500 – 800 m) are located locally in parts of the Rajang Group fold–thrust belts and in the central region consisting of the Hose Mountains and along the uplifted rims of the Dulit triangle in the north eastern part of the Rajang basin. In the Baram basin, the maximum local relief values are recorded in the dome-shaped Mount Mulu and south of the basin in the Rajang Group orogenic belts which mark the limit of the Interior Highlands of Borneo.

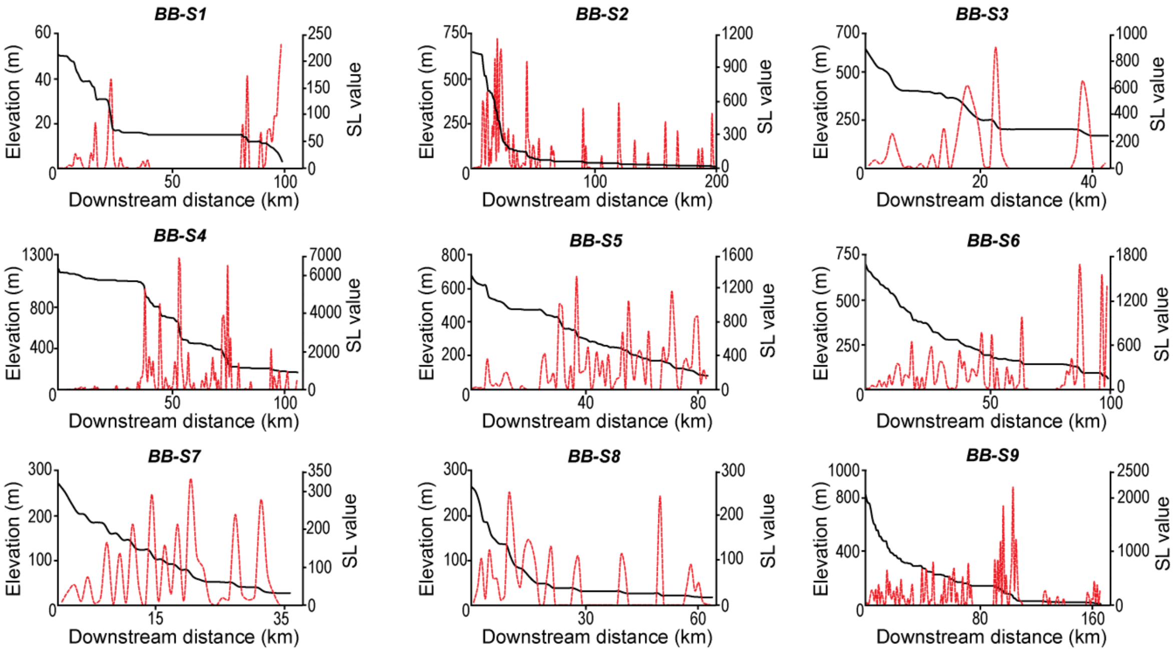


**Figure 4.6.** Stream longitudinal profiles and *SL* anomaly profiles of main tributary streams of the Baram drainage basin. High peaks of *SL* is noticed in the middle and downstream segments of the profiles without high values in the upper reaches. Note the flat upper reaches of BB-S2, BB-S4, BB-S5 and BB-S9. Main tributary streams used for analysis and knick-point locations are shown in figure 4.11.

The spatial distribution of relief anomaly values highlight locations of elevated and low relief landscapes located in north east and eastern parts of both Rajang basin and eastern parts of Baram basin (inset of Figure 4.11). It should be noted that the volcanic plateaus show relief anomalies due to its flat morphology. The factors governing the morphology of these plateaus are not the focus of this work and due to this reason the volcanic tablelands will be discarded from the interpretations of relief anomaly.

## 4.5.5 Field Campaigns

The field surveys revealed deeply incised V-shaped valleys, high-elevation low-relief surfaces, knick-points corresponding to waterfalls and terraced boulder to gravel sized fluvial deposits unconformably overlain above the incised basement rocks (Figures 4.3C, 4.3D and 4.12).

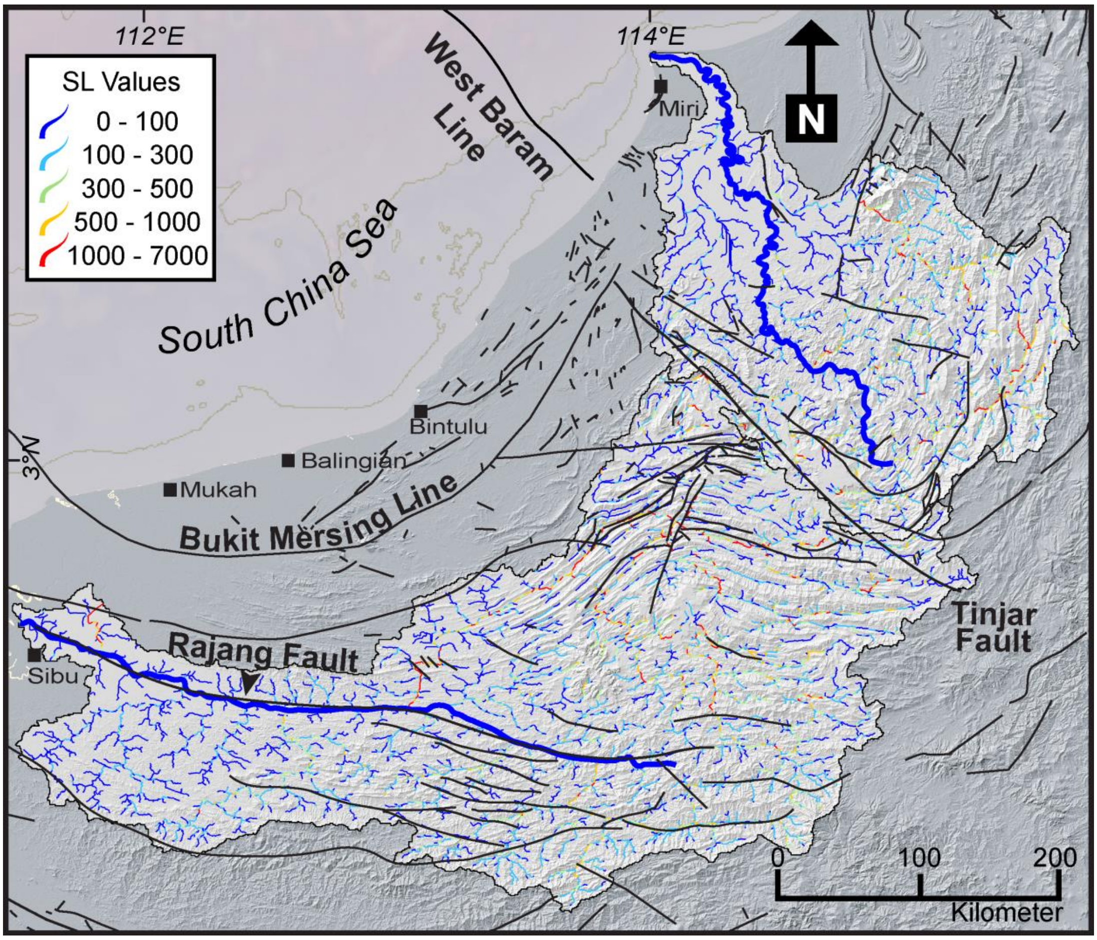


**Figure 4.7.** Color coded $SL$ index map of the drainage network of Rajang and Baram basins. Also shown are faults and structural lines following figure 4.2.

## 4.6 Discussion

### 4.6.1 Transient Landscape Evolution and Relative Contribution of Geomorphic Agents

Geomorphological and morphometric analysis were performed on two large drainage basins of north Borneo in order to elucidate neotectonic activity and the consequent geomorphic response to changes in boundary conditions.

The anomalous values of $SL$ obtained in this study are observed especially in RB-S8, BB-S3, BB-S4 and BB-S9 (Figure 4.7). $SL$ index is a surrogate of stream power per unit length ($\Omega$; $W\ m^{-1}$) (Font et al., 2010) defined by Summerfield (Summerfield, 2014). From this relation, it can be deduced that $SL$ has a first order dependence on channel slope gradients. Regions consisting of uniform lithology with high values of $SL$ indicates high channel steepness due

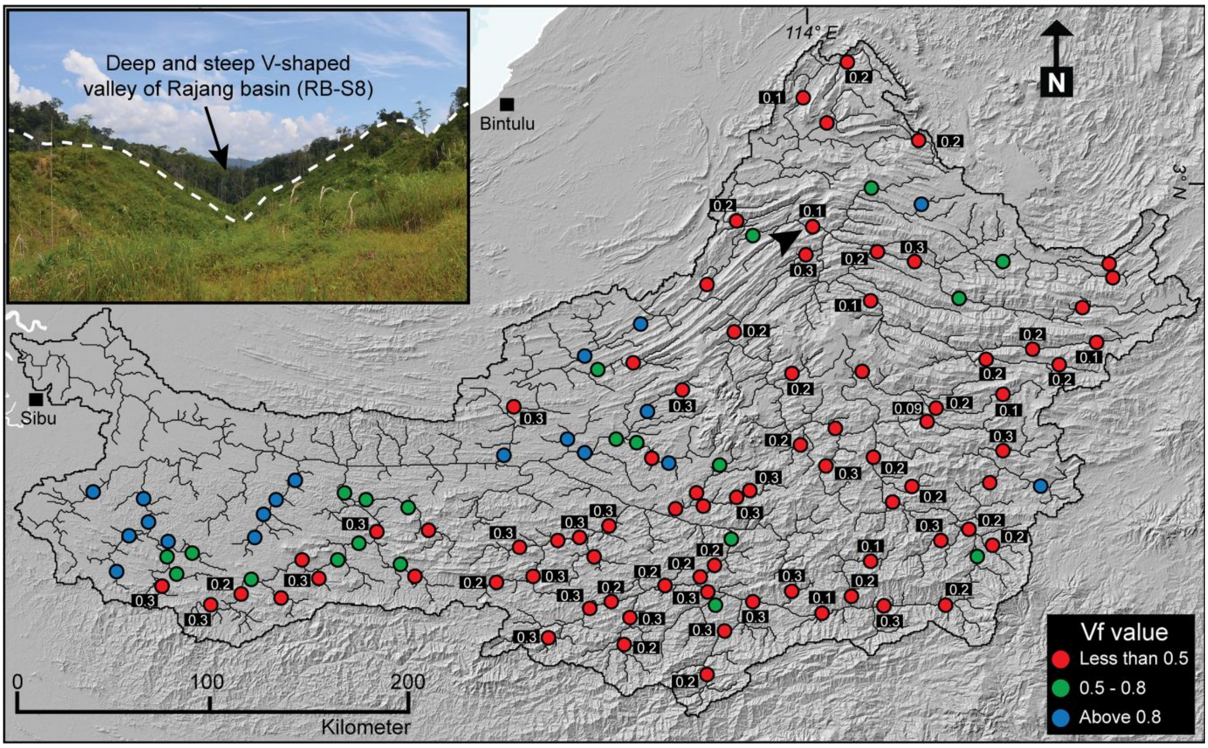


**Figure 4.8.** Locations of sections for the $V_f$ computation of Rajang drainage basin and anomalously low values of $V_f$ are appropriately indicated. At a glance, V-shaped valleys dominate the landscape of Rajang basin. Inset figure shows a field photograph of one of the numerous steep and deeply incised V-shaped valleys in RB-S8. Refer to figure 4.4C for vertical scale. Black arrow head indicates location of inset figure.

to recent tectonic activity and lesser values when flowing parallel to features such as valleys produced by strike-slip faulting (Dehbozorgi et al., 2010).

The longitudinal profiles of the rivers in sub-basins in RB-S8, BB-S3, BB-S4 and BB-S9 reveal prominent knick-zones showing topographic breaks and steps along the streams in the downstream and mid-reach segments (Figures 4.5, 4.6 and 4.11). Theoretically, the distribution of breaks can be influenced by tectonic uplift and/or faulting, contrasting bedrock lithology of hard and soft rocks, and Quaternary climatic perturbations inducing base level variations (Font et al., 2010). The basins RB-S8, BB-S3 and BB-S4 are located more than 300 km from the coast and the outlet is at elevations ranging ca. 75 – 200 m (Figure 4.5 and 4.6). Moreover, since the knick-zones are located at various elevations in adjacent sub-basins, there is no correlation with any narrow altitude range throughout the network. Due to this, we discard the possibility that the knick-zones in these sub-basins may have formed because of a fall in base-level due to Quaternary sea level fluctuations. Knick-zones corresponding to a number of waterfalls and/or faults were also observed in the field (Figures 4.12A, 4.12B, 4.12D and 4.12F). High values of $SL$ in RB-S8, BB-S3, BB-S4 and BB-S9 are congruent to

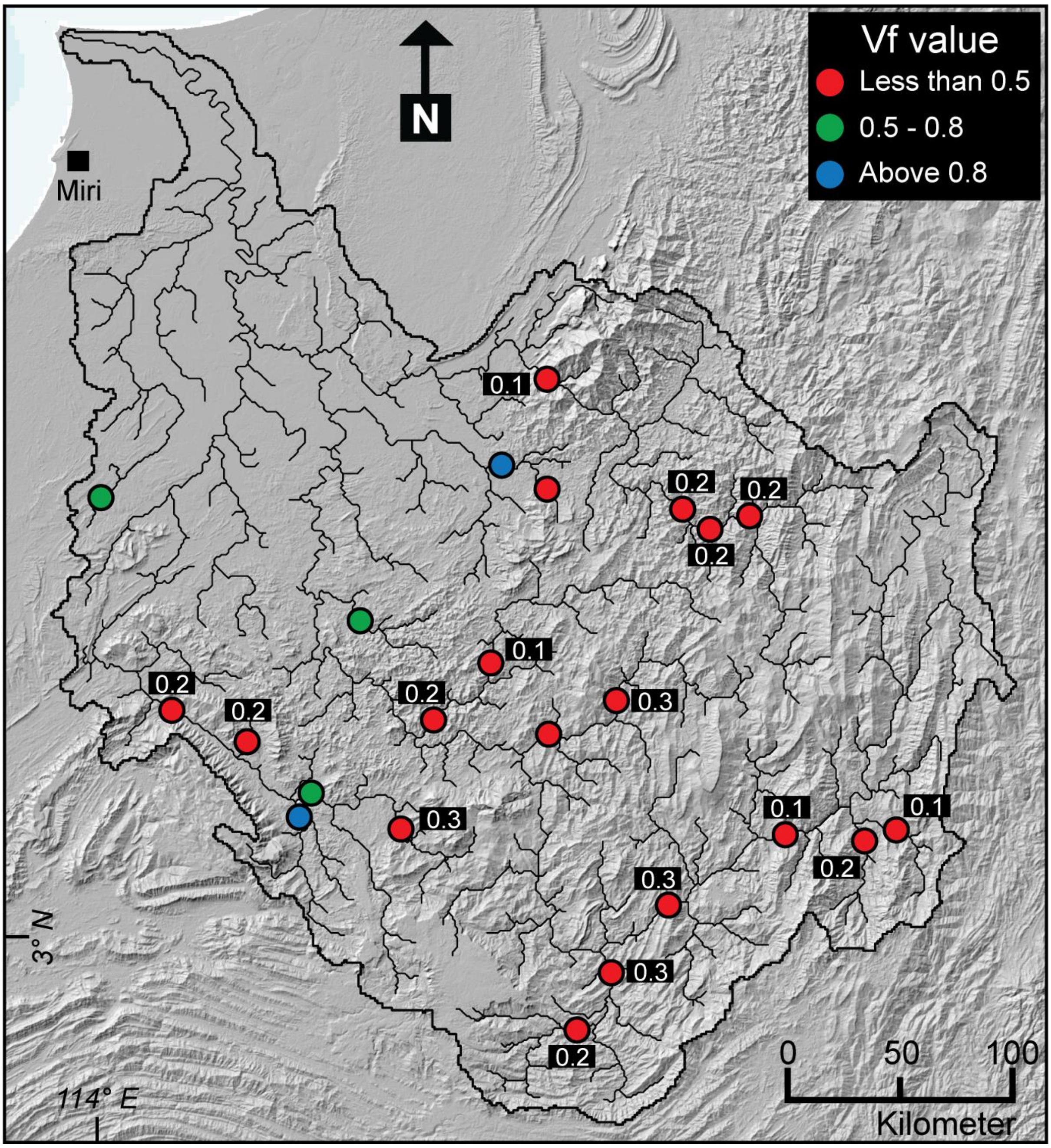


**Figure 4.9.** Locations of sections for the $V_f$ computation of Baram drainage basin and anomalously low values of $V_f$ are appropriately indicated. Note the distribution of V-shaped valleys are clustered in regions of complexly deformed topography.

deformed terrain of the Sarawak part of the Interior Highlands of Borneo and many of the steep gradients are consistent with known faults and structural lines in these sub-basins. The major tributary streams of these sub-basins flow over generally uniform lithology and formations (Figure 4.2) throughout mid-reaches to upstream segments. This information, together with the absence of major Quaternary base-level fluctuations, we interpret the anomalously high and low values of $SL$ (Figures 4.5, 4.6 and 4.7) in our results as indication

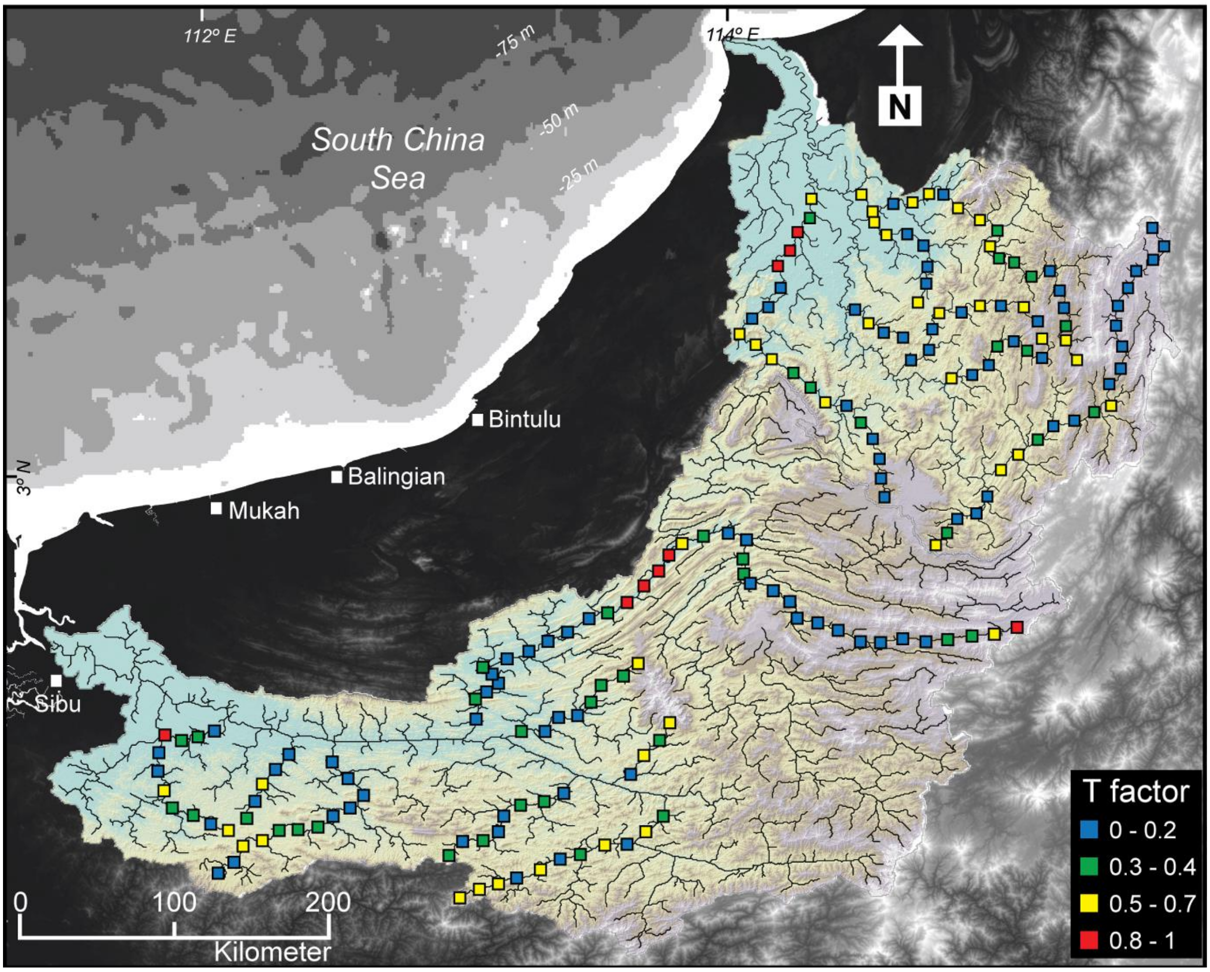


**Figure 4.10.** Transverse topographic symmetry factor for the studied drainage basins of north Borneo. The points indicate the locations of values extracted for computation of indices. Deflections of the drainage pattern are noticed subsequent to faulting and structural controls.

of having a tectonic origin. Our results also highlight a combination of trellis and dendritic drainage patterns in the regions affected by the Rajang Group thrust belts. Especially prominent are the headwaters of RB-S8 (southern headwaters), BB-S4 and BB-S9 showing dendritic drainage pattern. The trellis pattern is characteristic of fold–thrust belts meanwhile dendritic patterns form in homogenous terrain having very low surface gradients. Many streams in RB-S8, BB-S3, BB-S4 and BB-S9 appear to link both patterns through watergaps at high elevations while cutting across ridgelines with high $SL$ values (Figure 4.7).

The spatial correlation of $SL$ values with significant fluvial knick zones (Figures 4.5 and 4.6) and fault zones (Figure 4.7) in Rajang and Baram basins evidence the sensitivity of stream gradient to tectonic uplift. A combination of these factors reflects landscape transience in Sarawak as a response to tectonic forcing since a landscape in transience is characterized by

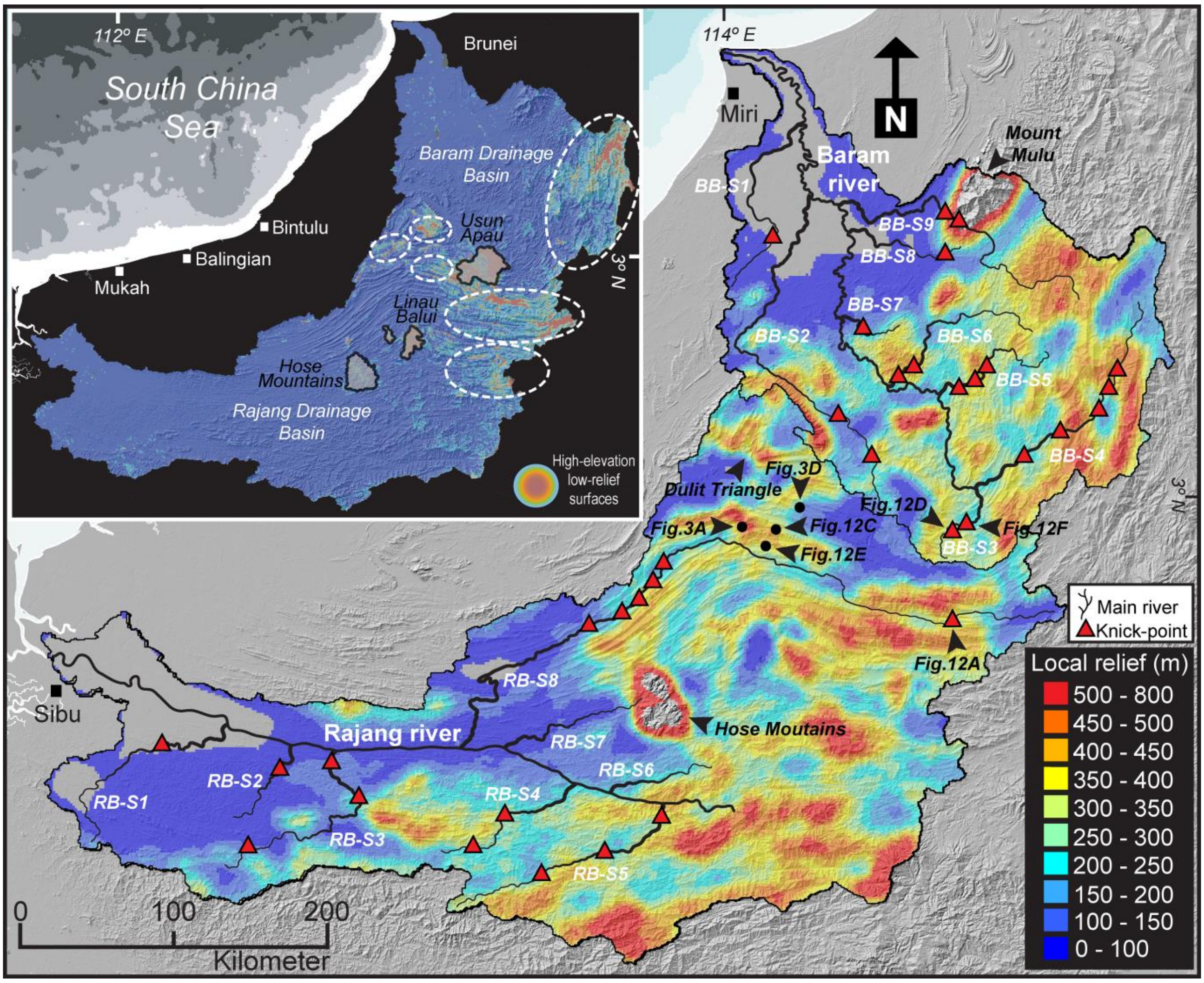


**Figure 4.11.** Local relief map of Rajang and Baram drainage basin constructed with an analysis grid consisting of cells having an area of 1 km$^2$ (see data and techniques). The map is draped over 30 m SRTM DEM to highlight the topography. High relief values mainly constitute locally parts of the Rajang Group thrust belts, the Hose Mountains, Dulit triangle and Mount Mulu. Inset map illustrates relief anomaly of both basins highlighting high-elevation low-relief surfaces indicated by white dashed ovals (see data and techniques and Fig. 4.3D). *SL* anomalies corresponding to figure 4.5 and 4.6 are shown along the main tributary streams used for analysis. Also shown are locations of Figure 4.3 (A and D) and 4.12.

migrating knick-points and knick-zones in the river profile created by tectonics as compared to static knick-points created by lithological contrasts (Whipple and Tucker, 1999; Bishop et al., 2005; Willett, 2006; Whittaker et al., 2007; Attal et al., 2008; Loget and Van Den Driessche, 2009; Gallen et al., 2013; Giletycz et al., 2015).

The response of a landscape to a change in tectonic uplift is dominated by an increase in channel and hillslope gradient, leading to an increase in stream power and incision capability of rivers. Landscape morphology and drainage evolution of both Rajang and Baram drainage basins can be quantitatively characterized by the incision style of the rivers. The present day


**Figure 4.12.** Field photographs of geomorphic features pertaining to topographic breaks or knick-points corresponding to waterfalls in RB-S5 and BB-S3 (A), (B), (D) and (F), and terraced boulder to gravel sized fluvial deposits unconformably overlain above the incised basement rocks of streams in RB-S8 (C) and (E). Refer to figure 4.11 for locations.

incision pattern observed in both basins shows active landscape dissection due to rapid down cutting by streams in most of the valleys with prominent V-shapes that is consistent with field observations (Figures 4.8 and 4.9). $V_f$ index is a proxy for active tectonics since uplift is associated with incision (El Hamdouni et al., 2008). Active incision by streams in response to tectonic deformation are responsible for the present-day morphology of the valleys in north Borneo and deflection of streams leading to a possible drainage reorganization and landscape rejuvenation. This inference is further substantiated by our results from $T$ factor analysis (Figure 4.10).

Our results describe a topography, albeit with high altitudes, is characterized by upland low-relief surfaces nested between ridges and in the regions of complex deformation (Figure 4.11). These are delimited by faults in Rajang (RB-S8) and Baram (BB-S3, BB-S4 and BB-S9) basins (Figure 4.2) and evidenced through field survey as well (Figure 4.3D). These elevation-accordant surfaces are preserved as relict surfaces in regions experiencing perturbations in tectonic uplift rates and fluvial erosion has not yet counterbalanced this uplift (Clark et al., 2005; Burbank and Anderson, 2011; Legrain et al., 2014; Giletycz et al., 2015). We interpret the observed high-elevation low-relief surfaces, preserved locally in the interior of the folded and thrusted ranges of Rajang and Baram basins, as relict portions of landscapes characterized by low amplitude relief. Upstream segments of channel longitudinal profiles of rivers draining the aforementioned sub-catchments along with others (Figures 4.5 and 4.6), record planation surfaces without prominent knick-points followed by mid-reach fluvial knick-zones. These characteristics suggest tectonic uplift of these relict surfaces separating a lower adjusting zone and the remnant portions of the drainage network. As a feedback to a dominant tectonic input, the topography exhibits progressively down-cutting streams creating steep valleys. This propagating front of river incision is a dynamic adjustment to counterbalance new base-level conditions, indicating that the landscape evidences a transient response to disequilibrium.

### 4.6.2 Implications on Regional Tectonism

Among the two basins studied, the Rajang River coincides with the Rajang fault while the trunk stream flows along the Tinjar fault (Figures 4.1 and 4.2) in the Baram drainage basin. The drainage divides between Rajang and Baram basins are delimited by the onshore Tinjar fault. The offshore West Baram discontinuity splits both zones into two major tectonic blocks that experience varying levels of tectonic activity (Cullen, 2010) (Figure 4.3). The ongoing tectonic activity causing recent uplift in Borneo may be attributed to regional compression or extension (Hall, 2013) and possible large-scale geodynamic mantle processes and as a response, the propagating wave of tectonic forcing reactivated these major faults along with a number of smaller pre-existent dislocation zones.

Onshore Sarawak, the main tectonic structures observable is compressional fold and thrusts producing crustal shortening. During the Miocene, compression was dominantly ubiquitous in large parts of offshore and onshore Sarawak resulting in folding. Central and southern Sabah experienced this phase of tectonism with a relatively stronger magnitude resulting in strong folding initiated through basement uplifts and wrench faulting (Darman and Sidi, 2000). This compressional regime may be linked to the first convergence of Australia and Southeast Asia at ca. 23 Ma. The oblique convergence may have been accommodated by both strike-slip faulting and crustal shortening.

By the end of the Miocene (ca. 5 Ma), Borneo had completely emerged with only ~10 % of present-day areal extent under water (Molnar and Cronin, 2015). Sarawak and north Sabah experienced a phase of deformation triggered by trough basement uplifts and wrench faulting during the Pliocene (Darman and Damit, 2003). Evidences of folding and thrusting as a result of these tectonic stages have been observed offshore by previous works (Cullen, 2010; Menier et al., 2014).

Long-term (2 Ma) base-level lowering estimated by Farrant et al. (1995) from limestone caves in Mulu, Sarawak showed results of 0.19 +0.03/ -0.04 mm $y^{-1}$. They correlated this base-level lowering with epirogenic uplift rates and suggested an uplift rate of 0.23 mm $y^{-1}$ for the surrounding Setap Shale. Assuming this uplift rate as constant since 5 Ma, it would yield a present day elevation of the low relief relict shallow marine Miocene deposits in the headwaters of the Baram basin (Figures 4.2 and 4.11) at ~1100 m. This calculated elevation coincides with the present-day elevation of this relict surface (Figure 4.1). However, for such estimations, very low to no denudation have to be speculated in order to preserve the entire bulk of uneroded landscape. This is not the case in Borneo where rapid erosion is estimated to have removed more than 6 km crust since the Neogene (Hall and Nichols, 2002); moreover, adjacent ridges within the same basin rise to elevations of exceeding 2000 m (Figure 4.1). Based on the above, we posit that by the end of the Miocene (~ 5 Ma), entire Borneo experienced a phase of rapid uplift (possibly due to proto–South China Sea slab break-off) either in multi-phased alternating high and low rates of uplift, or a single-phase rapid uplift that could have gradually slowed down to present-day rates estimated by Farrant et al. (1995). This rapid uplift rate could have altered the precipitation rates of entire Borneo through orographic effect resulting in a dense river network and local piracy events to organize the present-day drainage basins of Sarawak. Our interpretation is congruent with the conclusions of Molnar and Cronin (2015) that the mountains of Borneo are young (< 10 Ma) and the ranges could have grown in elevation in the past 5 Ma and the precipitation rates of tropical islands within the Maritime continent increased during the same time. The dense drainage network formed by exacerbated precipitation rates in Sarawak could have effectively removed (from the Sarawak part of the Interior Highlands) a covermass of Miocene shallow marine sequence that was deposited prior to the rapid uplift. This removal of Miocene covermass from the rapidly uplifting Interior Highlands could answer the preservation of Oligocene-Miocene sediments only in the coastal regions of Sarawak (Figure 4.2) owing to relatively lower elevations and smaller drainage basins (with relatively lower drainage density) in the coastal zones. However, local capture events while the present drainage basins were being organized (as a result of rapid tectonic uplift and increased orographic precipitation) could have left locally distributed isolated remnants of the covermass and underlying Oligocene deposits manifested as the high elevation low relief surfaces in our results (Figure 4.11) which were unable to erosionally balance the rapid uplift. These surfaces can form in-situ as a result of local piracy processes in transient landscapes as established by previous studies (e.g., Willett et al., 2014; Yang et al., 2015).

The newly organized stream network, after removing the covermass, could have then incised into the underlying Oligocene deposits and the Rajang fold–thrust belts indicating superposition with antecedence forming watergaps and windgaps as indicated by the results of $SL$ which shows discordant dendritic patterns in the headwaters of basins affected by folding and thrusting (Figure 4.7). The dendritic pattern also shows high values of $V_f$ implying broad flat-floored valleys in the southern headwaters and northern mid reaches of RB-S8 (Figure 4.8). These regions are characterized by low relief as seen in Figure 4.11.

Results from topographic analysis show regions maintaining high local relief within the fold–thrust belts (Figure 4.11) with high $SL$ values and knick-zones in the downstream to mid-reaches of the rivers (Figure 4.5, 4.6 and 4.7), and stream deflection (Figure 4.10) along with drainage reorganization to a trellis pattern through capture and piracy. These are diagnostic features of active folding where the tectonic signal and consequent upstream propagating erosional wave has not yet reached the headwaters (Holbrook and Schumm, 1999; Snyder et al., 2000; Lavé and Avouac, 2001; Hilley and Arrowsmith, 2008; Burbank and Anderson, 2011). It should also be noted that in regions experiencing high erosion rates such as Borneo, geomorphic response to tectonic deformation can be removed rather rapidly and uplift rates during recent phases (<5 Ma) should be very high in order to maintain a young topography that retain evidences of tectonic signals produced by these phases. Thus, through our results, it can be reasoned that Borneo undergoes tectonic deformation in the form of active shortening within the fold–thrust belts of the island that leads to resurgence of the Bornean landscape. This shortening could be accommodated by major faults such as the Tinjar Fault which runs across-strike of the fold–thrust belts and shows present-day motion along the fault (Simons et al., 2007). Active shortening and reactivation of major faults could have also led to reactivation of minor dislocations. Indeed, judging from the mean elevations of the highlands of Borneo, it may not be classified under zones experiencing high rates of crustal shortening. Therefore, as discussed above, the rates of deformation in Sarawak could be considerably lower since ca. 2 Ma and enhanced orographic precipitation after ca. 5 Ma could have increased erosional capabilities allowing the topography to quickly attain a transient stage in response to the initial rapid uplift experienced between ~ 5 Ma – ~ 2 Ma and the present-day active shortening. Indeed, timing of deformational events, rates of uplift and denudation could be better constrained with the implementation of cosmogenic nuclide techniques and numerical modeling. Within this setting in Sarawak, we conclude that fluvial erosion has not yet fully compensated the perturbations in tectonic boundary conditions and reflects transience in the present-day.

## 4.7 Conclusion

Through quantitative morphometric analysis emphasizing on hydrography and topography, we demonstrated the role of surface processes and topographic adjustment on landscape development in a tropical rainforest environment. The morphometric parameters indicate a transient response of the landscape to disequilibrium initiated by active tectonic forcing. Our results describe a topography in which rivers in Borneo are still adjusting to tectonic input. This adjustment is prominently evident in stream length-gradient, which show anomalously high and low values in the mid-reach and downstream segments of the streams. These values corresponding to topographic breaks or knick-zones in the analyzed streams are controlled by tectonic input as revealed in the channel longitudinal profiles. The landscape of north Borneo is characterized by actively incising rivers that give rise to deep and steep V-shaped valleys that are predominant signatures of active tectonics. Our analysis also revealed the presence of high-elevation low-relief surfaces that indicate relict portions of landscapes that were tectonically uplifted and preserved. These surfaces do not show prominent knick-zones in the upstream segments of channels draining them; however, river long profiles reveal mid-reach knick-zones indicative of adjustment related to new base-level conditions induced by uplift. During Upper Neogene Period (~ 5 Ma), Borneo could have experienced a major tectonic event leading to rapid uplift of possibly the whole Interior Highlands and coastal areas of Sarawak. This tectonic setting could have promoted orographic effect and along with the rapid uplift could have promoted capture and stream piracy events and resulted in a dynamic reorganization of the drainage network and preserved relic landscapes. This work had shown that deformation in the form of active folding is an ongoing process, perhaps at low rates. However, the altered orographic precipitation patterns post ~ 5 Ma has since intensified denudation and the possible deceleration of deformation rates after the rapid uplift phase has helped to quickly attain a state of topographic adjustment. Given these conditions, we conclude that the landscape of Borneo has undergone rejuvenation and demonstrates a transient geomorphic response as feedback to tectonic-climatic forcing.

*Chapter* 5

# The Geomorphic Evolution of Sarawak, North Borneo

Mathew, M., Menier, D., Ramkumar, M., Santosh, M., Siddiqui, N., 2016. *Geoscience Frontiers* (Submitted).

***Contents***



## 5.1 Introduction

Understanding the interplay among tectonic deformation, climate forcing, erosion and long-wavelength crustal responses to mass loading and unloading is pivotal in deciphering landscape evolution of a region. Although isolating and diagnosing the exclusive role of each process in sculpting a landscape at different time-scales may render uncertainties; channel incision and erosion have been documented to be augmented by combined relationships between tectonics and climate (e.g., Burbank and Anderson, 2001; Kirby et al., 2003; Kirby and Whipple, 2012, Hagipour and Burg, 2014). Thus, fluvial systems are sensitive to tectonic and/or climatic processes and the analysis of incision and erosional regimes of landscapes can be used as archives recording these processes (e.g., Schumm et al., 2000).

Borneo is the third largest island in the World and is shared by Malaysia (Sabah and Sarawak), Brunei and Indonesia (Kalimantan) (Figure 5.1). It is enveloped by vastly inaccessible tropical rainforests, hostile rugged mountainous terrain and deep valleys that effectively impede and restrain geological and geomorphological research in this region. Borneo has experienced an ever-wet climate since Early Miocene following the collision of the Australian Plate with the Eurasian Plate (Morley and Flenley, 1987; Sia et al., 2014). The island is characterized by remarkably high rates of denudation over the last 20 Ma (average minimum denudation rate of 326 m Ma-1) which, for the same period, can be compared to the Himalayas albeit the area of land above 100 m asl in Borneo is only one third of the area of the Himalayas (Hall and Nichols, 2002). Although much work has been done on the sedimentology and stratigraphy of Borneo, there exists a general scarcity of studies pertaining to geomorphic evolution and processes that govern ‘source to sink’ dynamics. Given the size of Borneo and its tectonic complexity, it would thus be fittingly imperative to analyze parts of the island having similar tectonic and stratigraphic history.

Here we demonstrate using conceptual models, the geomorphic evolution of Sarawak, north Borneo by a systematic geomorphic evaluation of two of the largest drainage basins of Borneo Island: Rajang and Baram basins (Figure 5.1). We combine our results from field sedimentology (stratigraphy), and quantitative and qualitative geomorphic assessment in order to elucidate the role of endogenic and exogenic processes affecting landscape evolution of Sarawak. Stratigraphic successions can be indicators of environments of deposition and could be used as analogs of local eustatic fluctuations. We extend classical field sedimentological analysis by the quantitative description of topographic and geomorphic characteristics of the basins, measured from digital elevation models (DEMs), which distinctly expresses spatial distribution of the controls of the fluvial system with regard to channel incision, erosion and deformation. The resulting model potentially highlights the

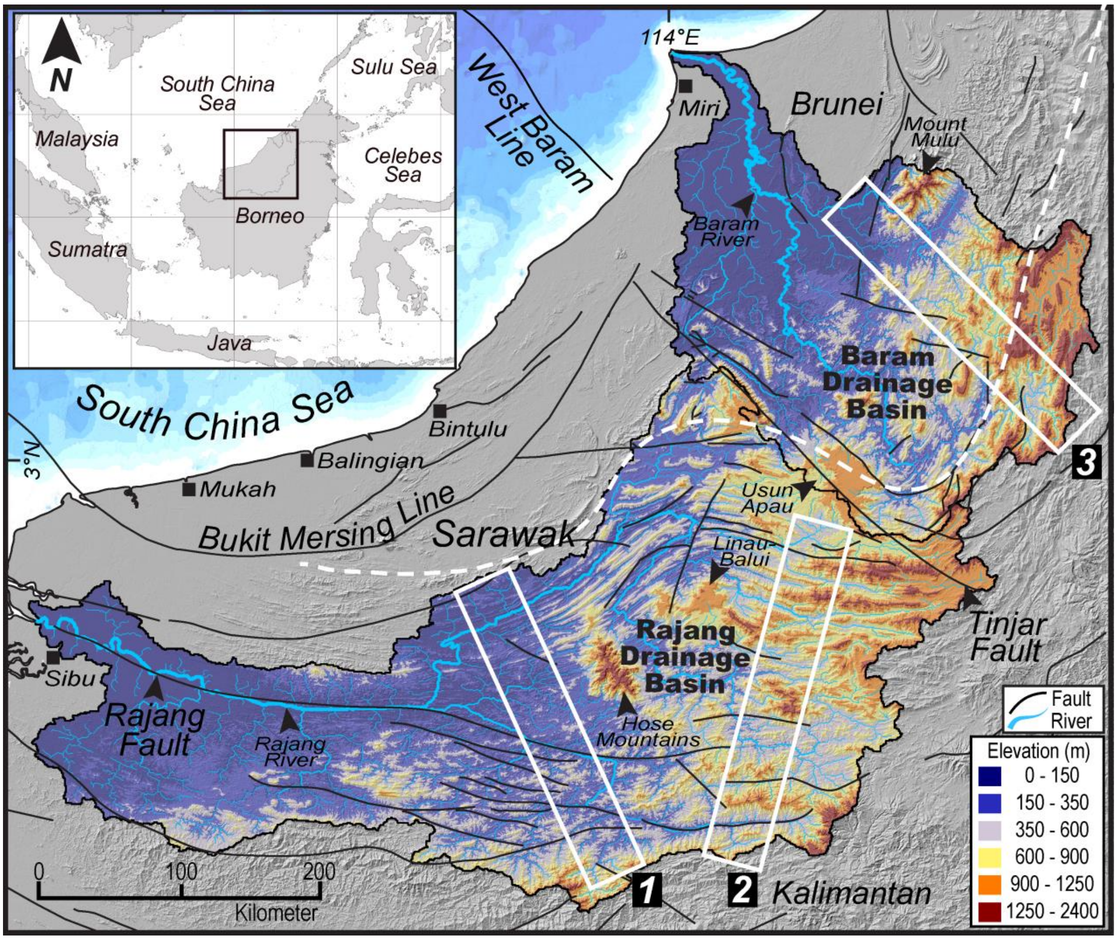


**Figure 5.1.** Shaded relief model of the study location of Rajang and Baram drainage basins of north Borneo. The drainage network is shown in blue solid lines and thickness is based on upstream drainage area. Also shown are some of the important highlands and tablelands of north Borneo. White dashed-line marks the approximate northern limit of the Interior Highlands of Borneo. White solid lines indicate rectangular swath profile windows.

processes responsible for denudation, sediment sourcing and deposition, and it could be integrated in tectonic evolution models at a regional scale.

## 5.2 Geological and Geomorphic Characteristics

Situated in the Sundaland core, Borneo is enveloped by tropical rainforests, mountains and deep valleys that effectively impede and restrain geological and geomorphological research in this region. Sarawak is one of the states belonging to Malaysia and is located on the Borneo Island. The east Malaysian state forms the northwest Borneo segment and borders the Malaysian state of Sabah to the northeast, the Indonesian state of Kalimantan to the south and surrounding the independent state of Brunei (Figure 5.1).

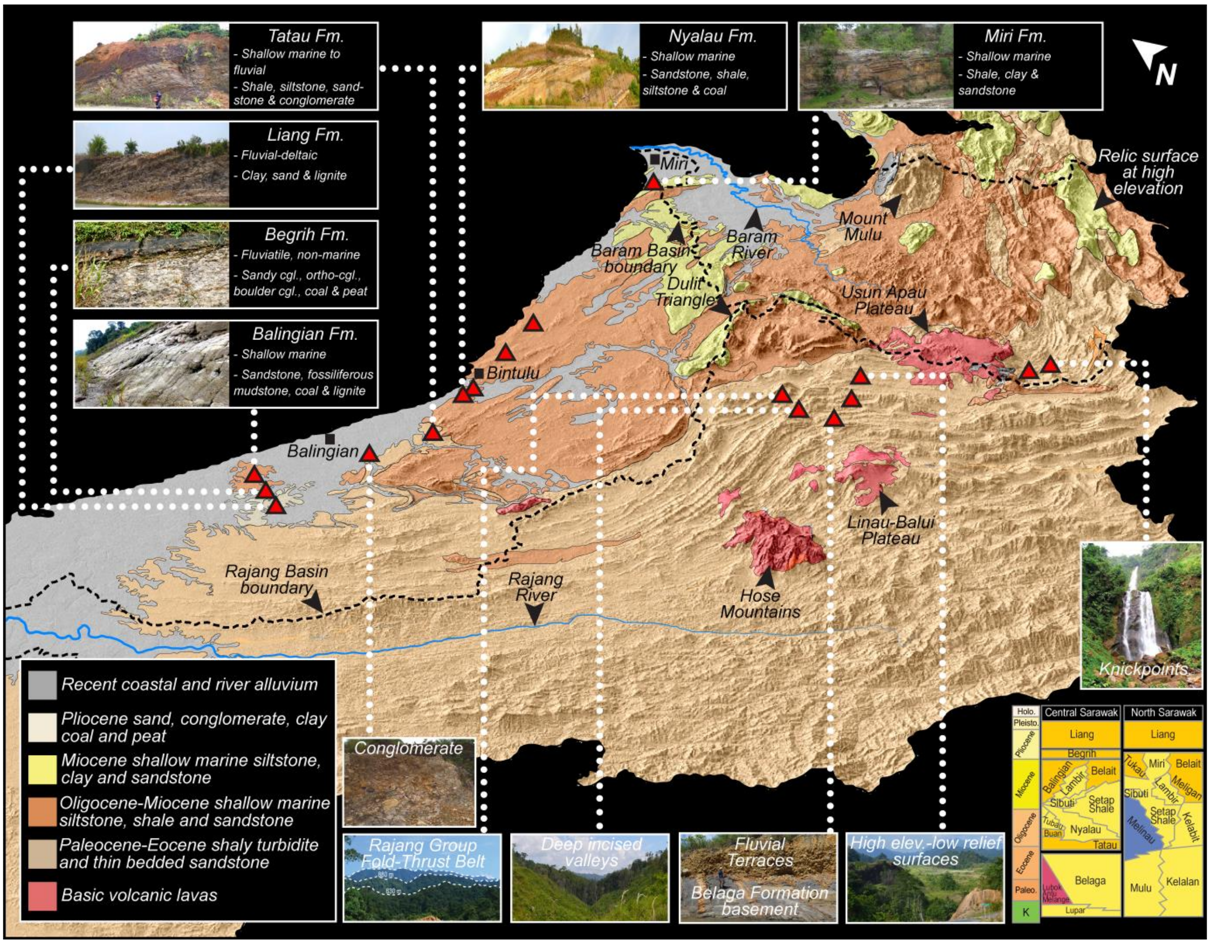


**Figure 5.2.** Perspective view of the geology of Sarawak. Red triangles denote some of the locations of fieldwork. Also shown is a general stratigraphic scheme of the central and north Sarawak.

Geologically, Sarawak can be divided into three distinct regions- west, central and north Sarawak (Tan, 1979). The studied basins: Rajang and Baram Basins drain the north and central parts of Sarawak. Both central and north zones are composed of sandstones, greywacke, shale, siltstone, clay (Hutchison, 2005; Siddiqui et al., 2015) and minor amounts of limestone and volcanic rocks ranging in age from late Cretaceous to Pliocene (Light et al., 1994) (Figure 5.2). In central and north Sarawak, structural trend lines run in broad curves. The central Sarawak terrain, covering the area between Lupar Line and the Bukit Mersing Line, is an arcuate fold and thrust belt called the Rajang Group Fold-Thrust belts that extend over a distance of < 1000 km along strike and a width of over 300 km (Tan, 1979; Williams et al., 1986) (Figure 5.2). This zone composed of the orogenic belt, named as Sibu Zone in Sarawak (Haile, 1974), forms the Sarawak part of the Interior Highlands of Borneo (Figure 5.1), and has been summarized as an Upper Cretaceous-Middle Eocene steeply dipping shaly turbidite with thin sandstone layers (Figure 5.2) (Wolfenden, 1960; Haile, 1962; Hutchison, 2010). The uplift of the Sibu Zone is interpreted to have occurred at the end of the Eocene, an event referred to as the ‘Sarawak Orogeny’ (Hutchison, 2005, 2010). The folds of this belt are described to be tight, overturned and broken by thrust faults (Tongkul 1987; Honza et al. 2000; Cullen, 2010) with at least one major thrust fault in between the formations within the Group. In Sarawak, an angular unconformity separates the Rajang Group from the overlying Oligocene-age shallow marine sediments (Cullen, 2010) (Figure 5.2). The geology of central and north Sarawak is younger than that of west Sarawak and special note must be taken that much of the geologic mapping of interior Borneo has been carried out only on a reconnaissance scale since access to the interiors is still logistically difficult (Hutchison, 2010). The Miocene sediments in Sarawak consist mainly of shallow marine successions of sandstone, siltstone and clay (Figure 5.2). The Mio-Pliocene formations consist of successions of clays, sandstones and very coarse to pebbly sandstone with local, boulder conglomerates at the base (Mat-Zin, 1996). Faulting and folding are common and appear to have affected all the rocks in the area except the Quaternary.

Since Early Miocene, Borneo has experienced a similar ever-wet climate (Hall and Nichols, 2002). Due to the abundant precipitation, Sarawak has an intricate drainage network that rise in the interior ranges and flow through deep gorges and rapids until they reach the coastal plains where they meander before draining into the South China Sea. Sarawak experiences a tropically hot and extremely humid equatorial climate and can be considered to be uniform at the scale of investigation. Annual mean temperature is of the order of 25° C – 32° C with a relative humidity of ~80 % for much of the year. Annual rainfall in Sarawak varies from 3500 mm yr-1 to 4600 mm yr-1, spanning 220 days an year with two monsoonal changes (Hua et al., 2013). An estimated 6 km of crust has been removed by erosion from Borneo during the Neogene due to high rates of weathering and erosion (Hall and Nichols, 2002). In terms of sediment yield, rapid removal of material by erosion makes Borneo Mountains comparable to mountain ranges such as the Alps or Himalayas (Hall and Nichols, 2002). A rapid erosional regime is induced with intense chemical weathering in majority of Sarawak.

The surficial topography of central Sarawak varies from terrain underlain by recessive shale through zones of linear ridges (interbedded sandstone and shale) to rugged highlands consisting of thick massive sandstones (Light et al., 1994; Siddiqui et al., 2015). In the interior of Sarawak, the landscape is dominated by a wide swath of discontinuous plateaus built of late Cenozoic volcanic and pyroclastic rocks (Figures 5.1 and 5.2). The Hose

Mountain Plateau, consisting of deeply dissected mesa, is about 32 km across rising to 2006 m rests on lower Miocene Nyalau Formation equivalent (Kirk, 1957). The Linau–Balui Plateaus covers 290 km2 and rises to 1127 m resting unconformably on folded Belaga Formation. It consists of a northern Tableland of 1100 m elevation and a larger southern Tableland of about 820 m elevation. The Usun Apau Plateau is about 906 km2 with small dissected volcanos that rise to 1372 m (Cullen et al., 2013). The plateau along with the Tinjar Fault separates the Baram and Rajang basins (Figure 5.1). The plateau has high cataracts and waterfalls spilling over its rim with plunges of more than 200 m (Hazenbroek and Morshidi, 2001; Cullen et al., 2013).It consists of an eastern Tableland of approximately 1000 m elevation and a smaller western Tableland of 760 m high (Hutchison, 2005). The Usun Apau and Linau–Balui volcanic plateaus and Hose Mountains are considered to be younger than 4 Ma (Cullen et al., 2013).

## 5.3 Materials and Methods

### 5.3.1 Swath Topographic Profiles

Elevation data of complex topographies can be condensed into a single profile (Duncan et al., 2003; Ponza et al., 2010). A rectangular swath of 25 km width was chosen to extract a series of parallel profiles that are separated by 1-cell (90 m). The width of the swath used in this work was chosen as it is large enough to appropriately condense both elevated surfaces and streams and on the other hand, is small enough to avoid averaging topographic structures that are too oblique to the axis of the rectangular swath. Statistical parameters such as maximum, minimum and mean elevations were calculated along each swath profile within a GIS environment. The plot for maximum elevation corresponds to the ridgelines and the curve for the minimum elevation depicts the valley floors or river beds. A measure for incision can be produced by the arithmetic difference between the maximum and minimum elevations within the longitudinal distance of the swath rectangle (Andreani and Gloaguen, 2016).

### 5.3.2 Minimum Bulk Erosion

The amount of eroded rock column and relative erosional stage of basins can be estimated by firstly envisaging a theoretical pre-incision surface. The raster map of this surface was constructed by interpolating elevations from the present-day drainage divide of the basins (Menendez et al., 2008) using GIS software. A minimum bulk erosion map was then constructed by subtracting elevation values contained in each cell of the pre-incision raster from the elevation values contained in each cell of a Digital Elevation Model (DEM). Indeed the ridgelines forming drainage divides themselves are subject to erosional processes (Brocklehurst and Whipple, 2002). Therefore, the resulting map will highlight the minimum amount of eroded-rock column and facilitate the discernment of under-eroded areas from areas subject to high erosion rates, thus allowing relative comparisons of erosional stages between basins.

### 5.3.3 $k_{sn}$ Anomaly

Normalized channel steepness index ($k_{sn}$) is used by us in order to determine the relative gradient of the channels (Safran et al., 2005). The slope–area regression has the following form (Flint, 1974)

$$S = k_s A^{-\theta}$$

where $S$ is the local channel slope, $k_s$ is the steepness index, $A$ is the upstream drainage area and $\theta$ is the channel concavity index. A normalized channel steepness index $k_{sn}$ is estimated by normalizing the catchment area of a given reach and using a reference concavity ($\theta_{ref}$) which corresponds to the regional concavity observed in reaches unperturbed by tectonic signals. The above equation can be re-written as

$$S = k_{sn} A^{-(\theta ref)}$$

A reference concavity ($\theta_{ref}$) of 0.45 was used for all channels to facilitate the comparison of our results. $\theta_{ref}$ of 0.45 was chosen as it is within the range commonly perceived in bedrock rivers regardless of rock uplift rates and erosion (Kirby and Whipple, 2001; Wobus et al., 2006).

We then constructed anomaly maps from the values of channel steepness index by using an ordinary krigging statistic method based on a variogram model. The resulting map highlights areas with maximum density of high steepness values relative to its neighboring cells.

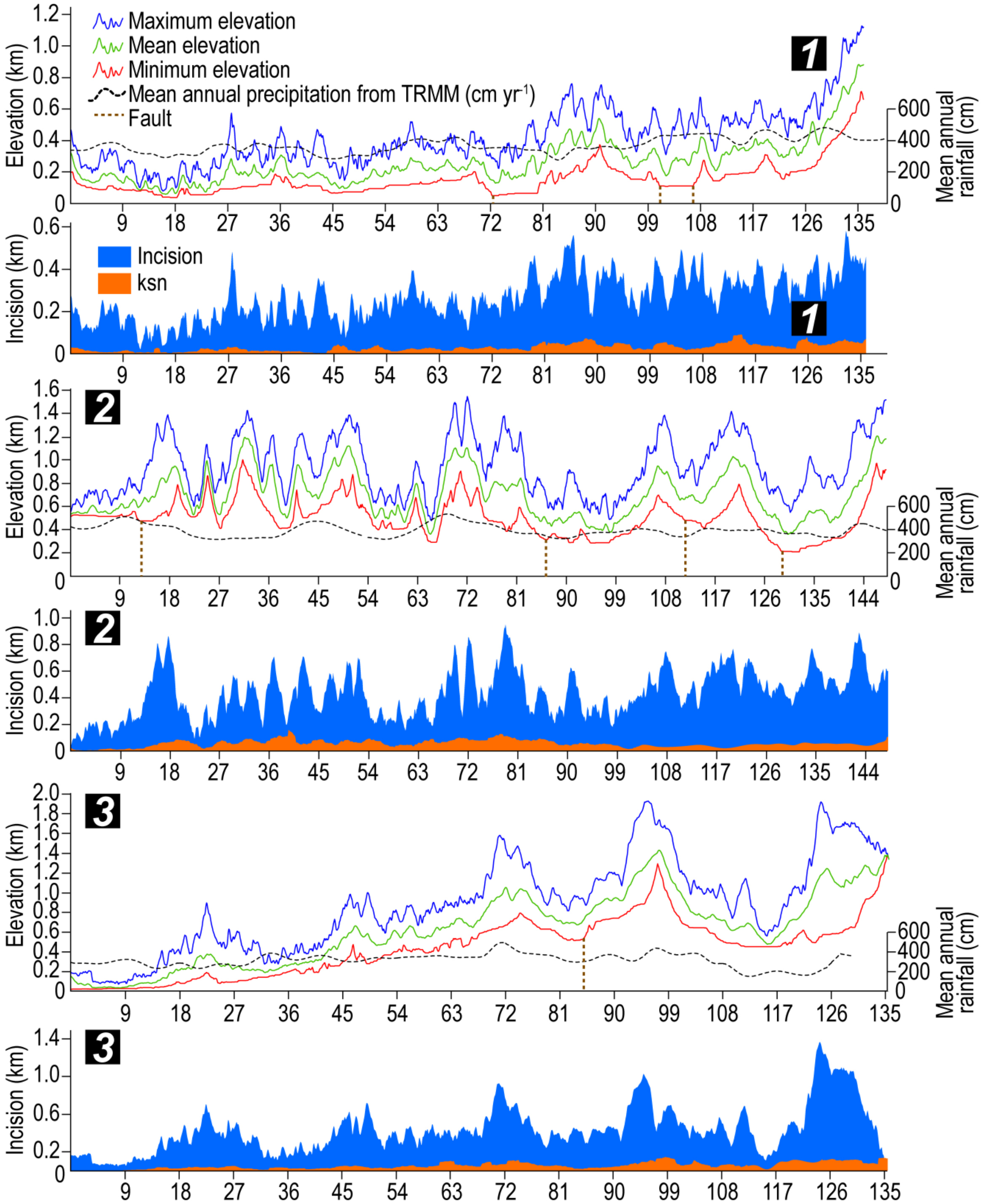


**Figure 5.3.** Swath profiles across the Rajang and Baram basins. Rectangular swath window is maintained at 25 km width. Blue, green and red curves in the line graph indicate maximum, mean and minimum elevation respectively. Blue histogram graph shows incision and orange histogram graphs indicate $k_{sn}$ values. Black dashed-lines identify mean annual precipitation rates derived from TRMM data. Note the elevation of the Interior Highlands increases from profile 1 to 3.

## 5.4 Results

### 5.4.1 Topographic Characteristics

We analyzed the topography of both Rajang and Baram drainage basins along three swath profiles (Figures 5.1 and 5.3). The maximum, minimum and mean elevation of each profile was extracted and annual averaged precipitation derived from the Tropical Rainfall Measuring Mission (TRMM), that was measured from 1998 – 2009 (Bookhagen, 2009), was plotted along with the elevation curves (Figure 5.3). The swaths in both basins are perpendicular to major ridgelines and valleys. Estimates of local incision were derived by subtracting the maximum and minimum elevation.

In the Rajang basin, profile 1 passes through the Rajang Fault located in the central section of the swath rectangle which coincides with the main trunk stream of the central valley of the basin: the Rajang River (Figure 5.1). The southern zones of the swath profiles encompass wrench faults and transform faults, and the profile in general covers the fold and thrust belts of the Rajang Group. The topography increases significantly from ~ 450 m in the northern side to ~ 1150 m in the southern side. The minimum elevation curve shows the floodplain of the Rajang River to illustrate a steep gradient to the northern side in comparison to the flood plains of the other valleys in the southern zone within the swath boundary. The mean elevation of the central valley is ~ 300 m and the local incision appears to be ~ 50 m. Incision rates increases considerably toward the southern parts of the profile with mean values ~ 100 m. Precipitation rates indicate peaks of orographic effects along ridgelines and rain shadow zones can be noticed in the inner parts of the valleys (Figure 5.3). Profile 2 comprises of topography covering major portions of the fold and thrust belts in the northern and central parts of the swath (Figure 5.1). Although the southern zone passes along the less folded topography showing low slope gradients as illustrated by the dendritic pattern drainage network (Figure 5.1), the elevation appears to maintain similar peaks from the north to the south (Figure 5.3). Incision patterns show prominent increase in the northern to central parts consisting of rivers controlled by faults and fold and thrust belts with mean local incision indicating values of ~ 100 m. Precipitation rates display spikes on topographic peaks indicating increased orographic precipitation and shadowing effect in the shielded zones of the valleys (Figure 5.3). It should be noticed that higher rainfall rates are recorded in the northern and central parts of the swath as compared to the southern zone.

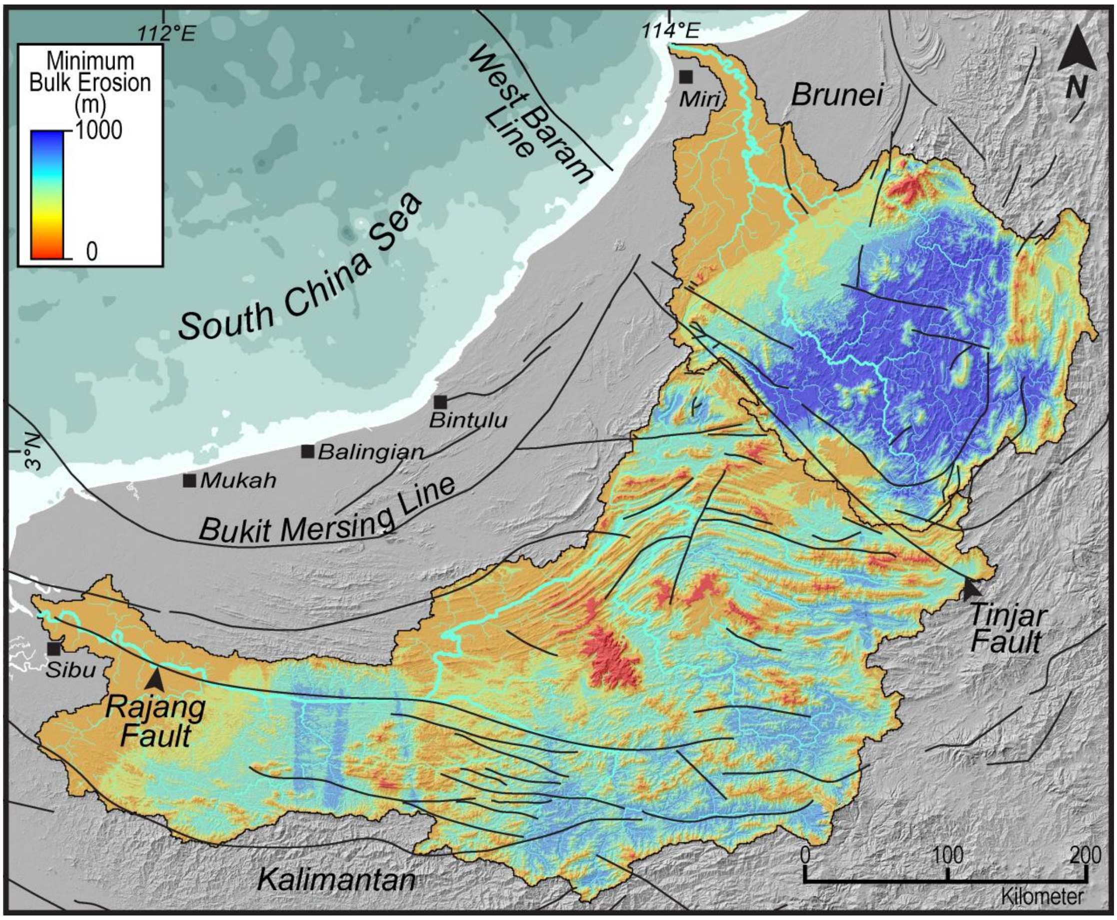


**Figure 5.4.** Minimum bulk erosion map showing the main streams and faults of the Rajang and Baram basins.

Within the profile 3 in the Baram basin (Figure 5.1), topographic elevations increase dramatically from ~ 400 m in the northern parts of profile 3 to ~ 1900 m in the southern parts and incision rates show significant increase in the same direction as well (Figure 5.3). It is noteworthy that the headwaters of the Baram basin show deeper incision as compared to the Rajang basin. Orographic rainfall rates increase as elevation rises with intermittent shadow zones in the valleys.

## 5.4.2 Relative Eroded Rock Column

Even a cursory examination of the minimum bulk erosion map reveals that the Baram basin shows a relatively larger volume of rock column being eroded from the headwaters and central parts of the basin as compared to the Rajang basin (Figure 5.4). Indeed the Baram basin hosts weakly eroded zones in the headwaters that belong to the Interior Highlands Rajang Group fold and thrust belts. The Rajang basin on the other hand, shows a lesser eroded topography with prominent under eroded zones along the thrust belts (Figure 5.4).

### 5.4.3 Normalized Channel Steepness Anomaly

Channel steepness index represents a metric of channel morphology and can define, qualitatively, zones characterized by variations in rates of channel incision. The anomaly maps constructed by us distinguish areas of high channel steepness from areas showing low steepness that reveal clear variations in both drainage basins (Figure 5.5). The map shows low values of steepness at the downstream segments of both basins. However, high values are recorded in the headwaters of the Rajang and Baram basins (Figure 5.5). Higher values are especially concentrated along the fold and thrust belts of the Interior Highlands Rajang Group. Fieldwork to accessible parts of both basins revealed knick points corresponding to a number of waterfalls and/or faults were observed along the segments showing high values (Figure 5.5).

### 5.4.4 Sedimentology Field Campaigns

Elaborate and comprehensive field campaigns were carried out between the years 2012 – 2015 to various locations in northern Borneo of which some of the studied locations in Sarawak are labeled in Figure 5.2. The objective of the field campaigns were to describe structural characteristics, facies characterization in order to elucidate the lateral extent of different lithofacies for stratigraphic correlation and interpreting depositional environments and ultimately integrating these datasets into a geomorphic evolution model. Some of the major stratigraphic units in Sarawak outcrop extensively along the coastal zones with good exposures of complete sections (Figures 5.2 and 5.6). Bearing in mind the objective and intend of this manuscript, only the main stratigraphic sequences of Sarawak will be discussed in this section.

The Upper Miocene, Lower Pliocene and Upper Pliocene sequences of Balingian, Begrih and Liang Formations outcrop in the Mukah – Balingian district (Figure 5.2). The Liang Formation (Upper Pliocene) consists of successions of clay and sand with abundant lignite and some tuff which were deposited in a shallow marine to coastal plain setting (Figure 5.2). The Begrih Formation (Lower Pliocene) contains abundant abandoned channel deposits with fine sandstone, laminated sandstone, ortho-conglomerates, sandy conglomerate and locally a boulder conglomerate at the base (Figure 5.2). The Formation also includes large amounts of coal and coal seams along with lignite beds. The deposits are interpreted to be of a continental fluviatile origin. The Balingian formation (Upper Miocene) consists of thick

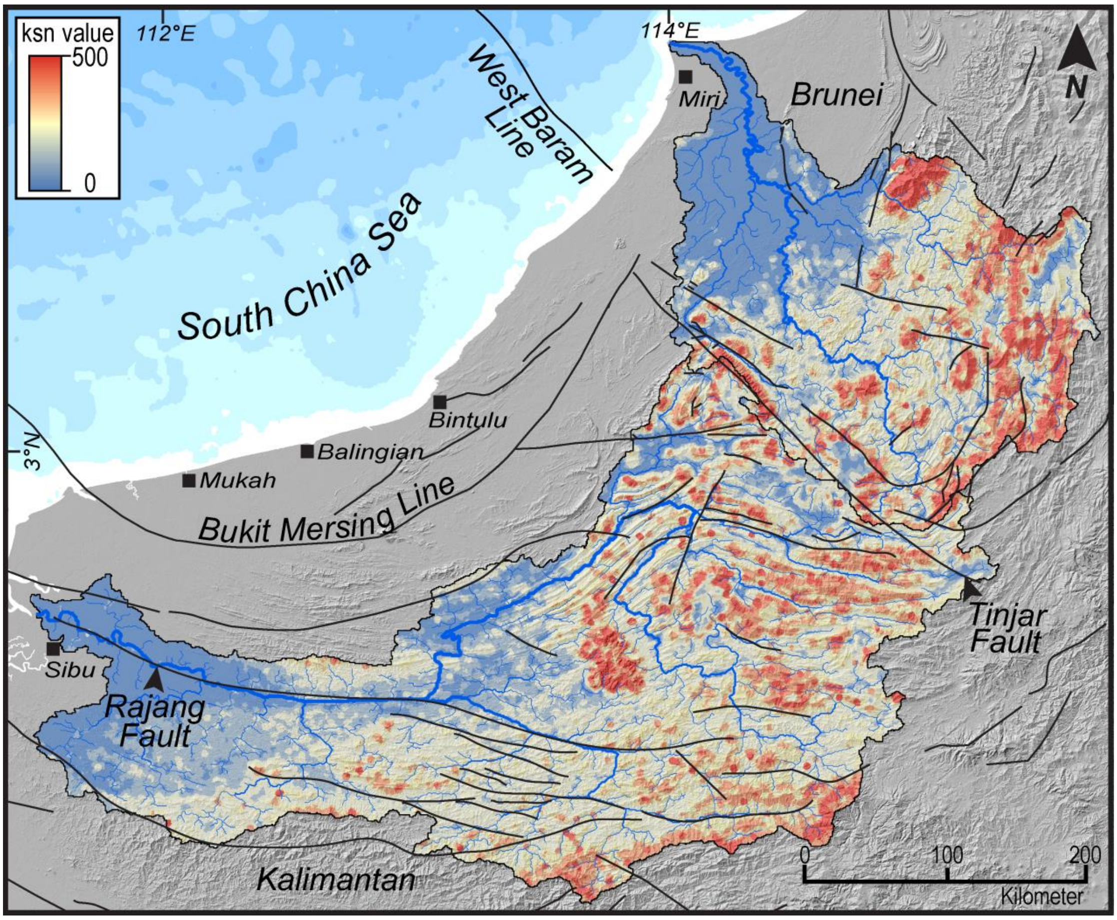


**Figure 5.5.** Ksn anomaly map indicating regions of high channel steepness. Note the congruence of high channel steepness with the known faults of Sarawak.

sandstone, mudstone, shale, siltstone and rare pebbly conglomerate beds (Figure 5.2). The formation hosts abundant coal and lignite beds, and is one of the largest coal mining sites in Sarawak. The Balingian Formation is interpreted to have been deposited in an estuarine to lagoonal environment.

The Middle – Late Miocene age Miri Formation outcrops around the Miri town (Figure 5.2 and 6). This Formation is one of the important oil bearing sedimentary strata offshore Sarawak. Miri Formation is predominantly argillaceous in the lower sequences and the upper succession is more arenaceous with thick sandstone beds and inter-bedded sandstone – shale. The Formation is interpreted to have been deposited within a shallow marine environment. For a detailed sedimentological and stratigraphic description with graphical logs, the reader is referred to Siddiqui et al. (2014).

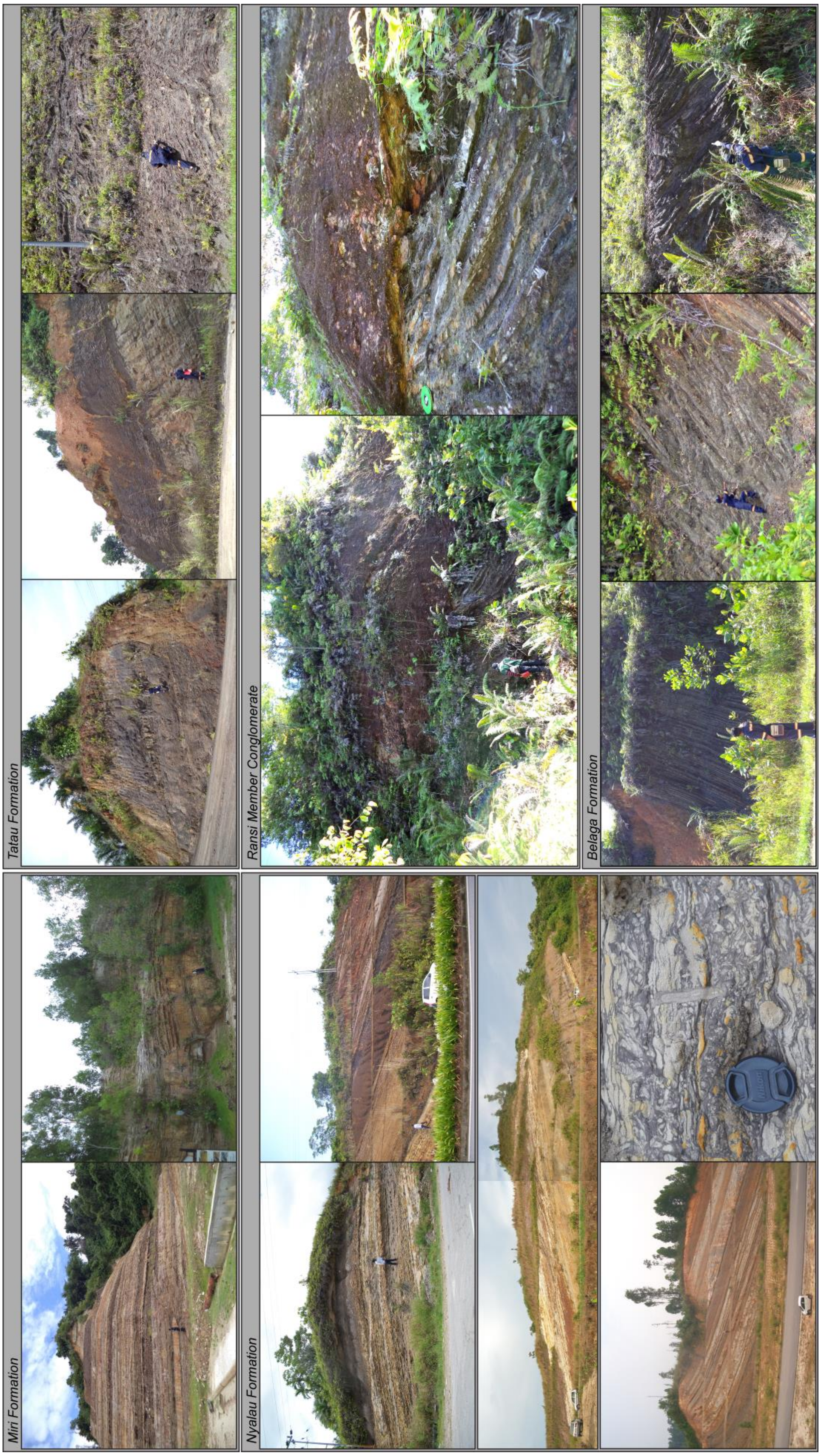


**Figure 5.6.** Field photographs on Miri, Nyalau, Tatau Ransi and Belaga Formation.

The Oligocene – Miocene (age derived from fossil records) Nyalau formation dominates the Bintulu region and to south of Bintulu, and along the Bintulu – Miri coastal road in the north (Figure 5.2 and 5.6). The Nyalau Formation is ~ 1000 – 2000 m thick sequences of shallow marine and paralic sedimentary rocks in Bintulu, predominantly consisting of heterolithic beds, cross bedded sandstones and coal-bearing mudstones. Coal is abundant and thin seams are interbedded with shale and sandstone at many localities. The Formation is gently to moderately folded and rests conformably on the Buan Formation and the upper boundary of the formation grades into the Setap Shale Formation (Figure 5.2). Bioturbation of vertical trace fossils particularly of Skolithos and Ophiomorpha ichnofacies is abundant within the Formation (Figure 5.6).

The Eocene – Oligocene Tatau Formation is considered to rest unconformably on the Rajang Group basement. The thickness of this Formation is measured to be 3000 m (Hutchison, 2005). The studied outcrops of the Tatau Formation consists of predominantly intensely folded carbonaceous shale and siltstone in the lower sequence, fine to medium grained sandstone and conglomerate beds (Figure 5.6). The Ransi Member conglomerates are found in the lower sequence of the Tatau Formation. The conglomerates overlie the basement rocks of the Belaga Formation of the Rajang Group with an angular unconformity (Figure 5.6).

The Eocene age Belaga Formation belongs to the Rajang Group that forms the major fold and thrust belt Interior Highlands that stretches from the northwestern and central parts of Sarawak to Sabah in the north (Figure 5.1 and Figure 5.2) and is dubbed as the backbone of Borneo. The analyzed Belaga Formation outcrops consists mainly of inter-bedded sandstones and shale and is tightly folded with near vertical overturned beds with the presence of numerous slump folds within larger fold limbs (Figure 5.6). The Belaga Formation is interpreted to be deposited in a deepwater turbiditic environment experiencing mass flows.

Fieldwork conducted in the interior parts of Sarawak revealed the presence of deeply incised V-shaped valleys, a number of knick points corresponding to waterfalls, cascades and cataracts, low relief relict surfaces perched at high elevations and terraced boulder to gravel sized fluvial deposits (Figure 5.2).

## 5.5 Discussion

### 5.5.1 The Geomorphic Evolution of Sarawak, north Borneo

We investigated the response of the topography of northern Borneo to perturbations in boundary conditions with regard to landscape evolution. Based on our results of geomorphic analysis, extensive field campaigns and, recent and previously published works, we show through conceptual models the topographic development of Sarawak, north Borneo emphasizing the controls of tectonic and climatic forcing on transient channel incision and erosion.

During mid-Eocene, the Semitau continental fragment from South China accreted to northern Borneo (Zahirovic et al., 2014) and this collision induced folding and thrusting of the Upper Cretaceous – Early Eocene Rajang Group shaly turbidite considered to be the basement sequence of northern Borneo (Figure 5.6). This orogenic event commencing with accretion/ collision could have attained maximum magnitude at ~ 37 Ma and was termed as "Sarawak Orogeny" by Hutchison (2010). The uplift of the Central Highlands of Borneo through crustal shortening may have exposed most of the landmass of Sarawak except for the zones covering the present day coastal plains which could have been areas of deposition of the Tatau Formation (Figure 5.2, Figure 5.6 and Figure 5.7). The record of this uplift event is witnessed in the Upper Eocene Melinau Limestone in Sarawak (Figure 5.2) and Sebuku Limestone in Kalimantan (Hutchison, 2010). The basal section of the Tatau Formation includes carbonaceous shale and siltstone with fine to medium grained quartz sandstone (Hutchison, 2005). The basal sequence also records tectonic deformation in the form of folding consistent with the folding and thrusting of the Rajang Group basement rocks (Figure 5.2 and Figure 5.6). The Tatau formation hosts rare conglomerate beds which could be related to the uplift causing exposure of more surface area for fluvial erosion.

The uplift of terrain during the Late Eocene would have caused a drop in base level and consequent shoreline retreat, and induced disequilibrium in the rivers, promoting active incision and deposition of the Lower Oligocene shallow marine sequences above the Eocene benthic deposits (Figure 5.7). Shoreline retreat would have exposed the shallow marine Eocene sequences which formed the continental zones during the Lower Oligocene. The exposed continental surfaces of Eocene deposits would have then been subjected to fluvial incision and erosional processes. The bedrock channels could have been in transience while

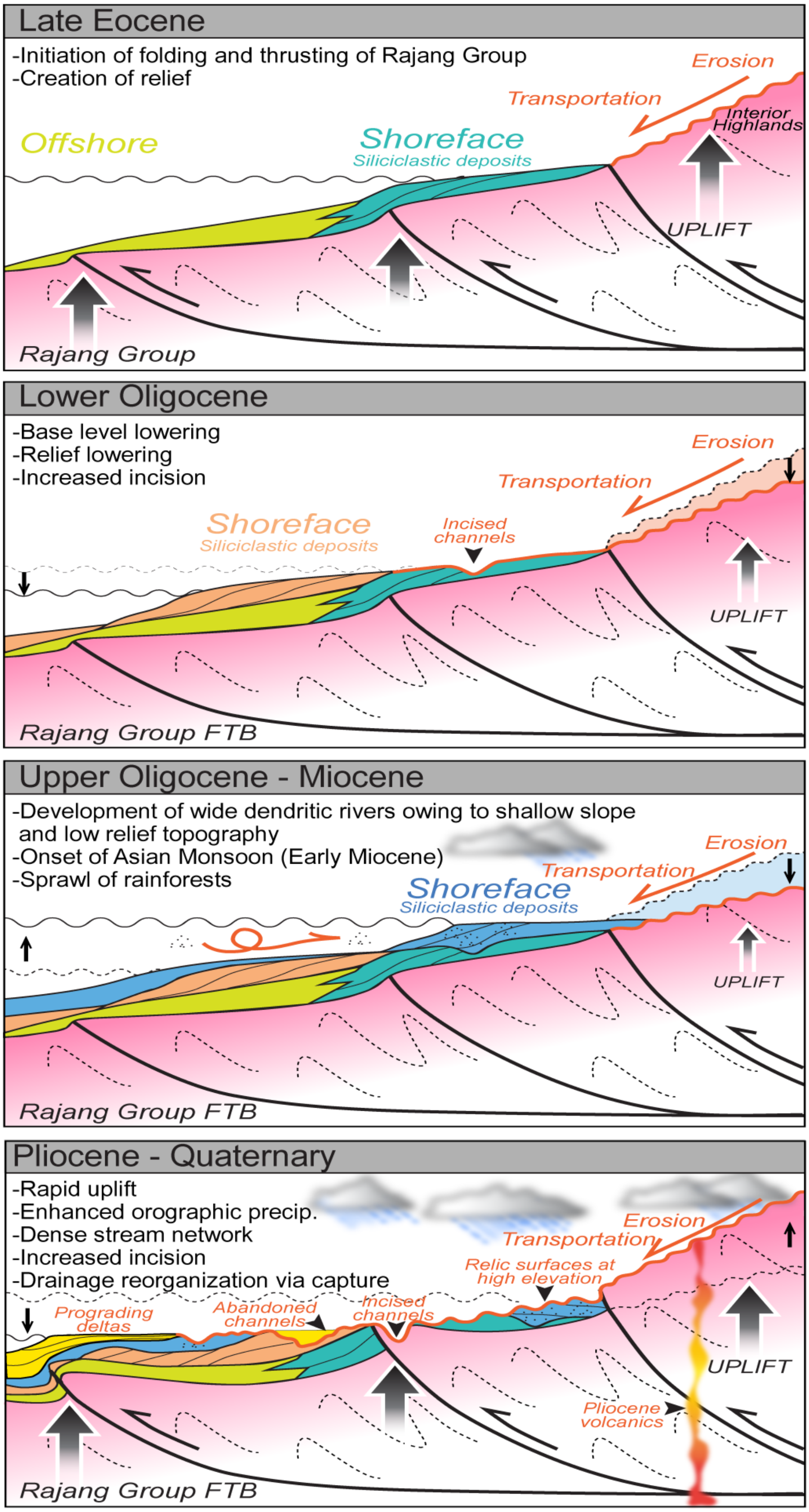


**Figure 5.7.** Conceptual model showing the geomorphic evolution of Sarawak, north Borneo.

adjusting to the tectonic input and trying to attain base level. Indeed, these surface processes proposed in our model are consistent with the Ransi Member conglomerate bed resting unconformably over the Eocene folded basement rocks (Figure 5.6). The Ransi Member conglomerates are epiclastic conglomerates generated by the breakdown of older rocks of the Rajang Group and are located in the lower part of the Tatau Formation (Wong, 2012).

Topographic adjustment would have been at its efficient best with rivers almost attaining a stable grade during the Oligocene when incipient rifting and initiation of seafloor spreading related to the opening of the South China Sea commenced in the Upper Oligocene (Zahirovic et al., 2014). These events caused rapid tectonic subsidence in the offshore and near-shore parts of Sarawak as documented by Mathew et al. (2014). Rapid subsidence would induce a local transgressive phase increasing accommodation space and altering local base level. Hall and Nichols (2002) report that at the beginning of Miocene, the area of Borneo above sea level was considerably smaller than at present and those marine sediments covered much of northern and eastern Borneo. The event of sea level rise forces shoreline and river-mouth backstepping along with shortening of streams (Blum and Hattier-Womack, 2009). The deposition of the Oligocene – Miocene sediments of the Nyalau formation (Figure 5.6) would have commenced during this phase with the hinterland supplying sediments as mean elevation of the Central Highlands dropped (Figure 5.7). During the Early Miocene, a major climatic change occurred following the collision of the Australian Plate with Sunda Plate (Sia et al., 2014). There was increased rainfall with the onset of the Asian monsoon due to the closure of the Indonesian Throughflow after the separation of the Indian and Pacific Oceans owing to the Australian Plate collision (Morley, 2003, 2006, 2012; Sun and Wang, 2005). Extensive development of rainforests commenced during this period which could have sourced the Miocene coals of the Mukah coal seams (Sia et al., 2014). Sia et al. (2014) showed from the architecture of the Mukah coal accumulated in the Balingian Formation (Figure 5.2) that there was rapid increase in depositional base level which supports the transgression proposed in our model. The increase in precipitation rates along with transgression would have led to widening of rivers with capability of transporting and depositing large amounts of sediments, and development of meanders and dendritic drainage networks characteristic of regions with low topographic slope devoid of structural controls. Relic Miocene shallow marine deposits with low relief can be witnessed as far as the Sarawak parts of the Interior Highlands (Figure 5.2). The Miocene deposits could have filled the incised channels formed on the previously continental surfaces that were exposed during the Lower Oligocene times, and thus forming a covermass of Miocene sediments. This postulation by us is coherent with and supported by the presence of the Ransi Member conglomerate bed overlain by the Nyalau Formation in the Bintulu – Tatau zone in Sarawak (Figure 5.6).

By the end of the Miocene, post 5 Ma, Mathew et al. (2016) showed that north Borneo experienced a phase of rapid uplift in polyphased or single-phase event. This rapid uplift resulted in enhanced orographic precipitation rates which in turn promoted the formation of a dense drainage network in Sarawak. This phase of uplift is also recorded in the subsidence curves constructed by Mathew et al. (2014) using near-shore wells in the Sarawak regions of South China Sea. Recent studies conducted by Molnar and Cronin (2015) on the growth of the islands of South East Asia including Borneo, showed that since 5 Ma, the mean elevation of mountain ranges in the islands have grown considerably and this in turn altered the climate through orographic effect. The tectonic uplift would have considerably lowered base levels and coupled with high rates of precipitation could have forced active and rapid channel incision. Rapid uplift and enhanced precipitation rates during this period could have reorganized the drainage network to the present day patterns as a result of piracy events (Mathew et al., 2016). The uplift of entire Sarawak could have promoted the development of superposed drainage networks with antecedence as seen in the Rajang Basin wherein transitional drainage patterns exist showing dendritic patterns adjacent to trellis patterns in the headwaters of the basin (Figure 5.1). The actively incising dense drainage network of Sarawak would have had the erosional capabilities to remove the covermass of Miocene sediments as progressive downcutting continued. The presence of isolated remnants of relic surfaces with low amplitude relief at high elevations of the Interior Highlands (Mathew et al., 2016) bears further evidence to the rapid uplift event and capture processes leaving isolated surfaces unable to erosionally balance the rates of uplift. The beheading and abandoning of channels owing to capture processes can be witnessed in the Pliocene Begrih Formation consisting of fluvatile conglomerates (Figure 5.2) and abandoned channel deposits. The sudden drop in base level and channel abandoning by capture may also produce lakes and mangrove swamps which can be sources of coal forming peat. Indeed, organic geochemical characteristics, palynological analysis and organic petrological analysis of the coals from the Begrih Formation and Liang Formation reveal a mangrove-derived source (Ni and Abdullah, 2004). The rapid erosion rates owing to tectonic-climatic forcing promoted the supply of Quaternary sediments to the offshore regions and aided in progradation of deltas around

Sarawak, especially the West Baram Delta which developed since Late Miocene – Quaternary. This inference is supported by the provenance analysis of sediments of the West Baram Delta which was found to be sourced from the erosion of uplifted sandy outcrops of the Nyalau Formation (Hutchison, 2005).

### 5.5.2 Transient Channel Incision as a Driver of Erosion Rates in Northern Borneo

There was a significant change in the patterns of sedimentation around Borneo in the Early Miocene (Hall and Nichols, 2002). The major delta systems of entire Borneo formed and prograded rapidly and enormous amounts of clastic sediments were deposited in the deep basins in the north and east of Borneo. Hall and Nichols (2002) opined that sediment volumes can be used to estimate the amount of crust removed by erosion using appropriate densities for sediments and consolidated crust. Using the above volume estimation, an average thickness of crust removed from Borneo would equal 6.5 km. However, these estimates were made using present-day erosional areas above 100 m elevation and according to Hall and Nichols (2002) this is unreasonable since the area above sea level during the Miocene was very small. From the present-day denudation area an average minimum denudation rate of 326 m $Ma^{-1}$ over the last 20 Ma and maximum denudation rates of 965 m $Ma^{-1}$ over the last 20 Ma is implied (Hall and Nichols, 2002). These rates can be compared to the Himalayas having an average minimum denudation rate of 383 m $Ma^{-1}$ and average maximum denudation rate of 950 m $Ma^{-1}$ over the last 20 Ma for the same present-day denudation area (Einsele, 1992). The thickness of the prograded Pliocene Baram Delta alone exceeds 6 km of clastic sediment (Rensbergen and Morley, 2003).

Based on the above discussion on rates and sediment thicknesses, our results and conceptual model of geomorphic evolution of north Borneo, we propose that following the rapid uplift of Sarawak after 5 Ma (Mathew et al., 2016) exposed additional topographic area for surface processes to work on and the present-day active folding of the Rajang Group thrust belts along with consequently high rates of rainfall combinedly contributed to high sedimentation rates around Borneo after Miocene.

Inferences gathered from $k_{sn}$ anomaly map (Figure 5.5) constructed in this study highlight regions having relatively high/ steep stream gradients which can be associated to a young topography owing to active folding and uplift of the Rajang Group thrust belts (Mathew et al., 2016). Rates of bedrock incision act as primary controls over long-term denudation rates of orogenic belts (Whipple, 2004). On the other hand, bedrock incision can be intensified by steepening of local stream gradients and spike in fluvial discharge rates. Conversely, in an actively uplifting topography, the hillslopes and corresponding channel gradients are thought to respond to river incision into bedrock by steepening to a maximum stable or ‘threshold’ angle (Larsen and Montgomery, 2012). Thus, it can be surmised that patterns of stream gradients in the studied basins act as proxies of relative bedrock incision rates. Our results demonstrate that channel steepness shows a relation of direct proportionality with incision in both basins, in that, when incision increases, subsequently channel steepness values escalate and concurrently display high orographic precipitation rates in zones of significant incision (Figure 5.3). The patterns of precipitous channel gradients are consistent with locations of deeply incised V-shaped valleys formed parallel to strike of the fold thrust belts identified by Mathew et al. (2016).

Results from minimum bulk erosion elucidate weakly eroded regions within both Rajang and Baram basins (Figure 5.4). Upon comparing the map showing minimum bulk erosion and the map of $k_{sn}$ anomaly, it can be observed that the weakly eroded areas coincide with high $k_{sn}$ values (Figure 5.3, Figure 5.4 and Figure 5.5) along with high incision rates. This is indicative of a recent tectonic input causing vertical crustal movement that in turn promoted a transient wave of incision to be introduced in the system. The occurrence of high bulk erosion values especially in Baram basin (Figure 5.4) could be related to continuous fault activity that could lower local base-level of streams allowing active incision and consequent erosion. Efficient local incision within the Baram basin is also evident from the swath profile showing high rates of incision in the headwaters of the basin (Figure 5.3) as compared to the Rajang basin.

We posit that there exists a coupling between tectonic and climate forcing such that it produces a positive feedback on transient channel incision that consecutively forces the topography to adjust by steepening hillslopes and channel gradients, and this feedback loop in tandem with active folding, in turn, significantly increased erosion rates in north Borneo after 5 Ma.

## 5.6 Conclusion

Through a combination of sedimentology and stratigraphy data obtained from extensive field campaigns and previously established works, and quantitative and qualitative geomorphic assessment of two of the largest drainage basins in Borneo, we showed the geomorphic evolution of Sarawak, north Borneo. The conceptual models constructed for the first time in this study highlights the various stages of geomorphic development with respect to exogenic and endogenic processes that govern 'source to sink' dynamics in Sarawak.

Late Eocene witnessed the "Sarawak Orogeny" owing to crustal shortening related to folding and thrusting initiated by the collision of the Semitau continental fragment from south China. The folding and thrusting exposed the Interior Highlands of Borneo while inducing regression that promoted active downcutting by streams subjected to disequilibrium by the drop in base level during the Lower Oligocene. Evidence of which is seen in the form of conglomerate beds resting unconformably over intensely folded turbiditic basement rocks of Eocene age in Sarawak. During Upper Oligocene times, offshore Borneo experience seafloor spreading related to the opening of the South China Sea. The rapid subsidence in the offshore and near-shore parts of Sarawak would have promoted a transgressive phase which is evidenced in Sarawak in the form of Oligocene – Miocene age shallow marine deposits covering large swathes of the region including the Sarawak part of the Interior Highlands. Concurrent to the submersion of large areas of Sarawak by shallow sea, there was the onset of the Asian Monsoon in the Early Miocene as a response to the collision between the Australian Plate and the Eurasian Plate. The increased rainfall would have promoted the widening of rivers leading to enhanced transportation and sedimentation capabilities to near-shore regions of Sarawak along with relief lowering. Abundant growth of rainforests and subsequent formation of lakes and peat swamps was widespread during the Miocene. At the end of Miocene, there could have been a major tectonic event leading to the rapid uplift of possibly the whole Interior Highlands and coastal areas of Sarawak. The creation of relief further enhanced precipitation rates through orographic effect resulting in disequilibrated stream networks reorganizing to attain a stable grade. The rapid uplift and drainage reorganization could have produced lakes and mangrove swamps capable of forming peat which could have indeed sourced the Pliocene coals in Sarawak. Enhanced erosion rates in Sarawak (post 5 Ma) led to rapid progradation of deltas and Plio–Quaternary sediments that reach thicknesses of above 6 km in the present-day. Our analysis indicates that as a result of these events, post 5 Ma, the topography has been adjusting to perturbations in boundary conditions. We suggest the onset of rapid erosion is due to a coupling between tectonic and climatic processes producing incision which in turn allows for topographic adjustment by regulating hillsopes and channel gradients.

# *Chapter* 6

# Conclusions and Recommendations

***Contents***



This chapter concludes the main finding with reference to specific objectives and some recommendations for future work. Here we try to answer what were the processes that acted and currently act on the landscape of north Borneo and sculpt it in the way it is today. The complex landscape of Borneo is indeed undergoing constant change and the topography pursues adjustment. The records of this can be witnessed in the high rates of erosion since Miocene times and drastic climatic variations induced by global influences and local topography since the same time.

The work in this thesis commenced with three objectives that firstly focuses on understanding the geomorphology of Sarawak situated in northern Borneo through morphotectonic analysis and substantial fieldwork to accessible parts of the heavily forested island. The second objective of the work involved analyzing the current stage the landscape of Borneo is experiencing and the thirdly to propose a geomorphic evolution model which takes into account sedimentation patterns and preservation of sediments. The main focus of this work is divided into three folds which are bonded with geomorphometric analysis of two of the largest drainage basins of Borneo: the Rajang and Baram Basin and landscape development with respect to factors controlling surface processes. In the following sections we conduct a synthesis of our main findings.

## 6.1 Active Tectonics of Sarawak

The tectono-geomorphic investigation conducted on Rajang and Baram drainage basins through morphometry reveal that the region has been subject to rapid tectonic uplift since 5 Ma which continues to present day. The topography shows signatures of active folding of the Rajang Group fold and thrust belts which constantly force the landscape into adjustment.

Hypsometric analysis of the drainage basins suggest that the basin includes areas with different degrees of dissection and indicates a young topography that is subject to rapid erosional regime. Hotspot analysis of hypsometric integrals indicating rapid drops in elevation and relatively under-eroded topography show high values along the fold and thrust belts of both basins containing uniform lithologies and climate conditions. High values of channel steepness were found to be congruent with the results of the hotspot analysis. Relict surfaces perched at high elevations was identified in the fold and thrust belts which demonstrated low amplitude relief and could be remnants of drainage reorganization which left areas unable to balance the rapid uplift rates. Both basins showed prominent tectonic tilting toward the direction of deformation and as a result showed highly asymmetric basins. The longitudinal channel profiles of many rivers draining both basins showed prominent knick-zones with no apparent lithological controls and in fact showed consistency with known fault zones. Fieldwork conducted to these zones revealed waterfalls and cataracts showing significant breaks in topography.

Bearing in mind the rapid erosion rates affecting Borneo, these expressions of tectonics could be maintained only if the topography is considerably young and are diagnostic of regions undergoing rapid tectonic uplift. Borneo could have experienced high rates of tectonic uplift since 5 Ma in a single phase or polyphased uplift with periods of fast and slow uplift in between.

## 6.2 Transient Stage of Landscape Development in Response to Disequilibrium

By considering the topography and hydrography, the current stage of landscape development in response to the tectonic input was deciphered. The landscape indicated a transient response to disequilibrium initiated by active tectonic forcing in which rivers in Borneo are still adjusting to tectonic input. Stream length gradient anomalies in the mid-reach and downstream segments of rivers show the propagation of incision toward the upstream segments promoted by perturbation indicate the migration of the wave of adjustment. The incision is also prominently visible in the deep and steep V-shaped valleys that were revealed during fieldwork to anomalous zones identified from our results. The rapid uplift rate identified through this work could have promoted orographic effect which increased precipitation rates in Borneo and this hypothesis is supported by other studies conducted in the region (e.g., Molnar and Cronin, 2015). The altered orographic precipitation patterns post ~ 5 Ma has since intensified denudation and this has helped to quickly attain a state of topographic adjustment. Given these conditions, we conclude that the landscape of Borneo has undergone rejuvenation and demonstrates a transient geomorphic response as feedback to tectonic-climatic forcing.

## 6.3 Geomorphic Evolution of north Borneo

Through a combination of sedimentology and stratigraphy data obtained from extensive field campaigns and quantitative and qualitative geomorphic assessment of two of the largest drainage basins in Borneo, we showed the geomorphic evolution of Sarawak, north Borneo. The models highlight the various stages of geomorphic development with respect to exogenic and endogenic processes that govern ‘source to sink’ dynamics in Sarawak.

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Australian Plate and the Eurasian Plate. The increased rainfall would have promoted the widening of rivers leading to enhanced transportation and sedimentation capabilities to near-shore regions of Sarawak along with relief lowering. Abundant growth of rainforests and subsequent formation of lakes and peat swamps was widespread during the Miocene. At the end of Miocene, there could have been a major tectonic event leading to the rapid uplift of possibly the whole Interior Highlands and coastal areas of Sarawak. The creation of relief further enhanced precipitation rates through orographic effect resulting in disequilibrated stream networks reorganizing to attain a stable grade. The rapid uplift and drainage reorganization could have produced lakes and mangrove swamps capable of forming peat which could have indeed sourced the Pliocene coals in Sarawak. Enhanced erosion rates in Sarawak (post 5 Ma) led to rapid progradation of deltas and Plio–Quaternary sediments that reach thicknesses of above 6 km in the present-day. Our analysis indicates that as a result of these events, post 5 Ma, the topography has been adjusting to perturbations in boundary conditions. We suggest the onset of rapid erosion is due to a coupling between tectonic and climatic processes producing incision which in turn allows for topographic adjustment by regulating hillsopes and channel gradients.

## 6.4 Recommendations

The work presented herein can be advanced and improved with acquisition of cosmogenic nuclide dating of river terraces and bedrock. The dating of such sediments would give us reliable constraints on timing of deformational events, erosion rates and rates of epirogenic uplift. The work presented by us proves the complex interaction of tectonic-climatic forcing on the Borneo landscape and can be used as reconnaissance results in order to conduct field work. However, there still remains the reservation and restrain in the form of inaccessible rainforests that post an undeniable and valid threat to any interested geologists. The work may be developed with the improvement of logistical conditions in Borneo and exposure of more outcrops. Nevertheless, it must be noted that the construction of numerical models open promising perspectives and valuable insights into landscape evolution. The models can be tested using various input parameters which give the user flexibility for an empirical and pragmatic approach. Such models may strengthen the current and future work in this region with limited field data.

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## Abstract

Geomorphic assessment of a region is considered to be crucial in understanding the present day landscape and forces that have acted and is currently acting on the ever evolving topography. This thesis explores the geomorphology of the tropical landscape of Sarawak, north Borneo through morphotectonic analysis of two of the largest drainage basins of the entire Borneo Island: the Rajang and Baram basin; making this work the first systematic tectono-geomorphic evaluation of the region. The island of Borneo is enveloped by thick rainforests, hostile rugged mountainous terrain with deep and steep valleys, and is characterized by high denudation rates since Miocene. The studied drainage basins flow across entire central and north Sarawak and drain a total combined area of ca. 75, 000 $km^2$. The first contribution to the field is by conducting a study on the presence of active tectonic forces that modify the topography through rejuvenation of major and minor faults. The analysis using basin-scale hypsometry, asymmetry factor, normalized channel steepness index and spatial autocorrelation techniques showed that the landscape has been rejuvenated and experiences tectonic deformation to present-day in the form of active folding of the fold-thrust orogenic belts of the Interior Highlands which form the backbone of Borneo. From the results, we highlighted the presence of relict surfaces of landscapes which were isolated at high elevations unable to balance a rapid uplift phase experienced after 5 Ma. We extended the study in order to identify the current stage of landscape development by conducting stream profile analysis which displayed an array of knick-zones and knick points devoid of lithological and climatic controls. Deep V-shaped valleys formed in the zones that demonstrated active folding of the highlands also revealed relief anomalies highlighted through topographic analysis. We showed that enhanced orographic precipitation following the rapid creation of relief has supported adjustment of the topography to a state of transience. In the next part of this work, we conducted swath profile analysis, minimum bulk erosion and channel steepness anomaly maps in order to identify the role of rapid incision in exacerbating erosion rates as a response to tectonic and climatic forcing. We show that there exists a coupling between incision rates, precipitation and channel steepness which shows a relation of direct proportionality. Extensive geomorphic and sedimentological field campaigns were carried out in order to substantiate our results and conclusions. The field work revealed the presence of uplifted fluvial terraces, waterfalls and cataracts corresponding to knick-points identified by us. Finally, we combine our results from the geomorphic

analysis and stratigraphic field work in order to construct a conceptual model showing the geomorphic evolution of Sarawak, north Borneo.