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Active tectonic deformation along rejuvenated faults in tropical Borneo: Inferences obtained from tectono-geomorphic evaluation

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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, for 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, the asymmetry factor and the 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 $m^{0.9}$) 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 knickzones 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 experiences active folding of 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 intermittent pulses of high and low uplift rates.

1. 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 using 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, 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, 2010; Font 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 (Fig. 1). It is characterized by unusually high rates of denudation over the last

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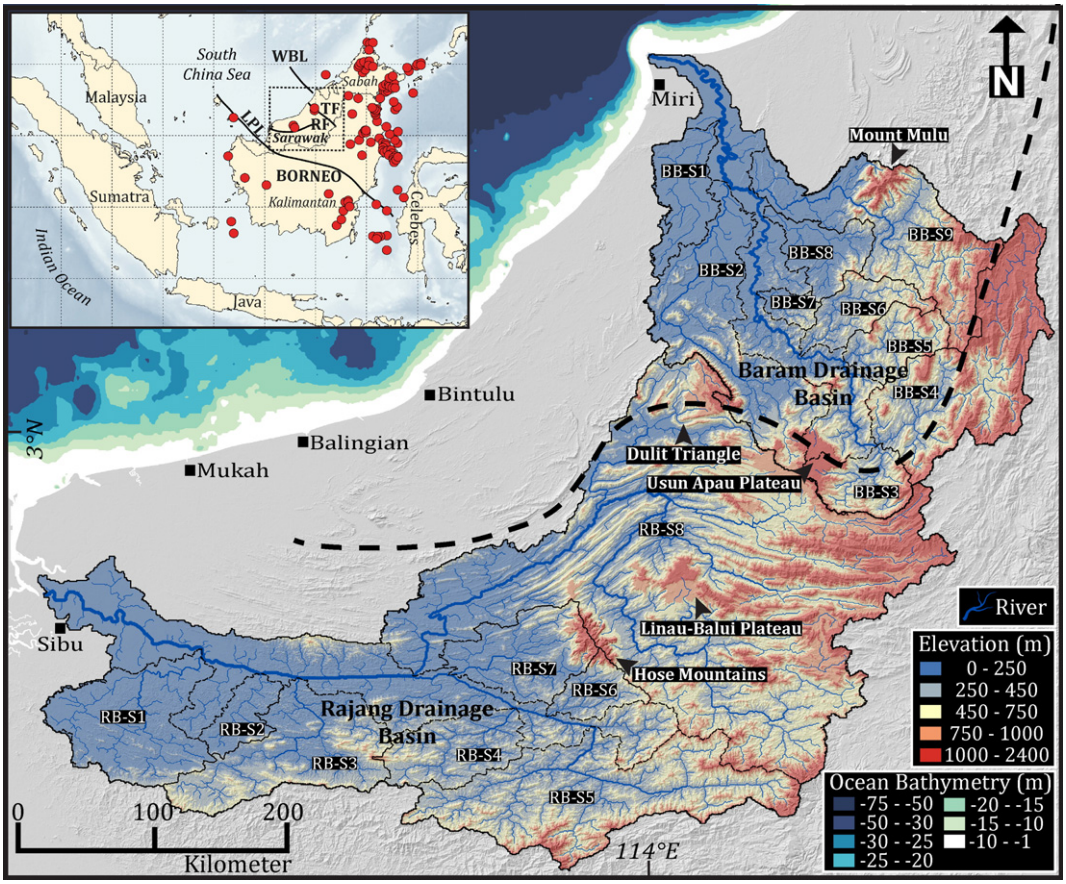

Fig. 1. Two largest catchments of Sarawak, north Borneo: Rajang and Baram basins. Both basins drain extensive regions of central and northern Sarawak. Sub-catchments of Rajang basin (RB-S1 – RB-S8) and Baram basin (BB-S1 – BB-S9) are numbered and catchment boundaries are demarcated by black thin dashed lines. Drainage patterns are illustrated in blue color and thickness is based on upstream drainage area. Black thick dashed-line indicates approximate limit of the Interior Highlands of Borneo. Inset map shows the location of major faults in the study area: 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. Red circles denote areas of recent seismicity (1960–2014).

20 Ma (average minimum denudation rate of 326 m Ma^{-1}) as a result 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 (Fig. 1). On the contrary, Sarawak, bordering Sabah and Kalimantan, indicates a sparse distribution of seismicity occurring from 1960 to 2015 (http://earthquake.usgs.gov/earthquakes/) (Fig. 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, 2014; Kessler, 2010; Kessler and Jong, 2011; 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 nearshore seismic sections have shown tectonic activity locally during the Pleistocene/Holocene border (Kessler and Jong, 2011, 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} (Fig. 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 (Fig. 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, the 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).