Tectonic Geomorphology of NW Borneo, Malaysia

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1. Introduction

The regional tectonic map of northwest Borneo indicates its position within an active network of plate boundaries of the Sunda, Indo-Australian, and Philippine Sea plates (Fig. 1A). The earthquake distribution shows seismicity clusters surrounding NW Borneo, which are largely along the active subduction zones. However, the small number of earthquakes recorded in NW Borneo could suggest that it is currently located far from the active plate margins and largely shielded from active plate tectonic movements (e.g. Hall, 2013). The earthquake moment tensor data shows dominance of shallow focused (5 to 13 km) normal and strike-slip faults, which indicates that crustal deformation is ongoing but apparently slower than on the neighbouring plate margins. The prominent structural and topographical expression of mountains, as well as the orientation of Holocene sediment-filled valleys in the region also suggests active faulting (Fig. 1B). The topographic expression of these intermontane valleys is near parallel to the strike of the active Crocker fault system, which could suggest that these small basins are a product of active faulting in the region, which needs explanation. Although the occurrence of earthquakes in NW Borneo is scarce, the shallow rupture depths suggest a shallow nature of crustal faulting, which could be related to either tectonic or gravitational forcing, or a combination of the two. This problem could be partially solved if careful and detailed mapping of geomorphic landforms is done by using digital elevation data, which is largely missing in previous works (e.g. Wang et al., 2016; Wang et al., 2017, Mustafar et al., 2017; Tongkul, 2017). Therefore, this work uses 30 m shutter radar topography extensively to map the geomorphic features of active faulting, including triangular facets, fault scarps, topographic breaks, bedding, etc.

2. Summary of the Active tectonic framework of NW Borneo

The study area (Fig. 1) is surrounded by the active tectonic boundaries of the Eurasian, Indo-Australian, and Pacific-Philippines Sea plates (Fig. 1). The continuous interaction of the plates occurs at variable rates, which over the geological past has produced a network of active structures that largely dictate the topographic framework of the region. Thus, the onshore and offshore geomorphology and topography preserve evidence and chronology of the geological past (Simons et al., 2007, Shah, 2013). The region is relatively far-off (e.g. ~800 km in the east) from the active plate margins (Fig. 1) and the evidence for active plate convergence at the Borneo-Palawan Trough is not satisfactory, which is why it is not considered a plate boundary in the plate tectonic map of the world (Bird, 2003). Therefore, the cause of active faulting in NW Borneo has largely remained divided into two major suggestions, which are related to gravity, and gravity plus tectonics (e.g. Ingram et al., 2004; Hesse et al., 2009; Sapin et al., 2013; Wang et al., 2017,

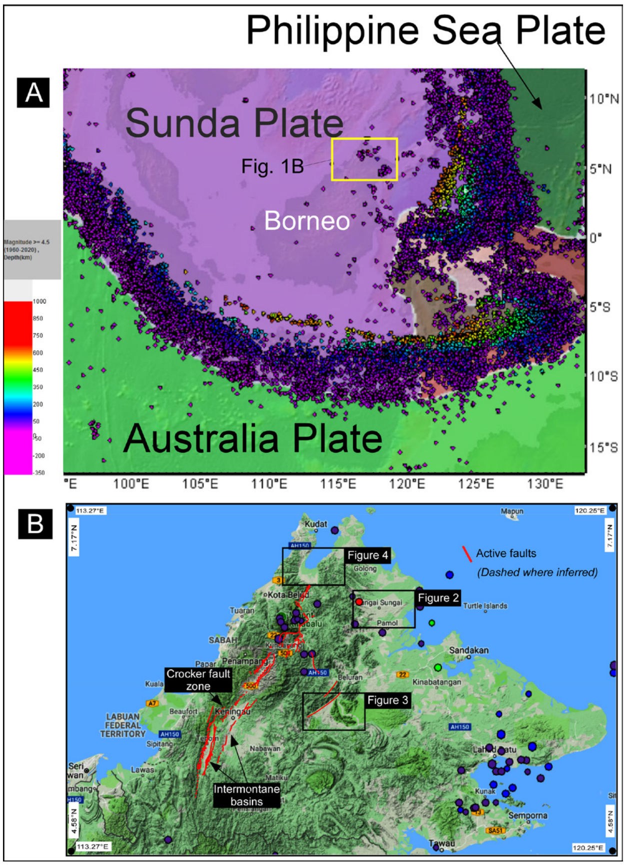

Figure 1: (A) The regional tectonic map shows the location of Borneo in the middle of active tectonic plates (plate boundaries after Bird, 2003) and the coloured dots are earthquakes; (B) shows the Google satellite image with three specific study locations in NW Borneo that are mapped in detail (see Figs. 2-4). It also shows the earthquake distribution across the region. Image extracted from IRIS Earthquake Browser on 25th March 2020.

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Tongkul, 2017; Shah et al., 2018, Wu et al., 2020; Navakanesh et al., in press). The previously mapped active faults in the region are mainly related to normal, thrust, and strike-slip faults (e.g. Shah, 2016; Wang et al., 2016; Wang et al., 2017, Mustafar et al., 2017; Navakanesh et al., 2019). The active normal fault system (known as Crocker fault system) has hosted a moderate-sized (M_w 6.0) earthquake on 5th June 2015, in Ranau, Sabah, which caused significant loss of life. Furthermore, on 8th March 2018, another moderate-sized (M_w 5.2) earthquake occurred on the same fault system. These events were shallow focus and ruptured the crust at 10 to 13 km depth. The pattern of faulting in NW Borneo is consistent with the fanning of the major strike-slip fault system that runs through the middle of Borneo Island that was envisaged by Shah et al. (2018) but the sense could be dextral.

3. Methodology

Geoscientists have extensively used remote sensing data to map geologic and geomorphic landforms (e.g. Molnar and Tapponnier, 1978; Nakata, 1989; Taylor and Yin, 2009; Shah, 2013; Shah & Malik, 2017). These studies have increased our understanding of the geologic, geomorphic, and tectonic architecture of different regions (e.g. Taponnier and Molnar, 1997; Molnar and Tapponnier, 1978). Field investigations are one of the major components of active fault mapping and for the collection of primary data on the geological, structural, and topographic settings of the region. Complementarily, satellite data are particularly important for regional studies and are useful in areas where fieldwork is impossible or difficult (e.g. Shah et al., 2018). The geomorphic analysis presented here uses a 30 m shuttle radar topography. The mapping is done by looking for evidence for faulting, which includes tracing of ridge crests to observe sudden changes, which could be related to faulting (e.g. Fig. 2). Triangular facets are a useful tool to investigate the active landforms and are used to map the bedding planes, aided by the rule of “V’s”, in which river valleys “V” towards the dip direction of the beds (Figs. 2-4). This rule is a very useful indicator where bedding dip direction is not known (Shah et al., 2018), and it works best for structural mapping on high-resolution images or maps. The technique is simple: rock beds interact with river erosion at various angles, which are usually a reflection of the dip angle, and the beds form triangular facets and valleys (e.g. Fig. 2-4) as erosion progresses, which makes the rule of “V’s” a robust tool to know the dip direction of beds or fault.

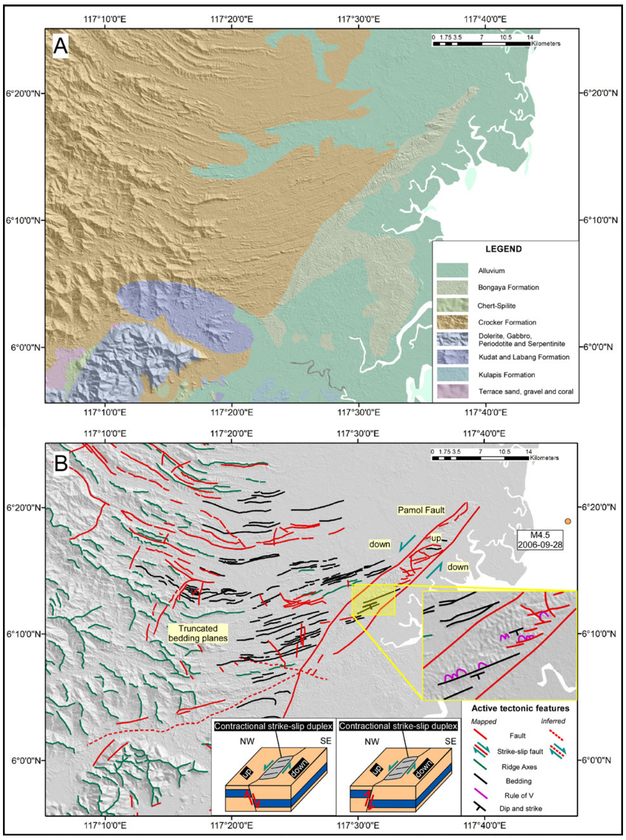

Figure 2: (A) Uninterpreted 30 m SRTM image with geology overlaid on it; (B) Interpreted image shows the various geologic and geomorphic features that are used as evidence for faulting. The contractional duplex feature is interpreted, and 3-dimensional illustrations are shown to explain the formation of the duplex with both normal (left illustration) and reverse (right illustration) fault geometries. We think the left illustration is representative of the fault zone.

4. Results and Interpretation

Three key areas (Fig. 1B) are studied in detail (Figs. 2–4). The rectangular windows in Fig. 1B show the extent of these areas of investigation. The lithological boundaries are mapped in Fig. 2B, and it shows the changes in bedding strike from ~E-W to ~NE-SW. This transition is sharp at the abrupt appearance of a chain of discontinuous ridges (Fig. 2B). The beds are truncated by ridges that exposed the Bongaya Formation, which are relatively younger rocks than the Crocker Formation that is exposed in much of the region under study. We have mapped this sharp truncation as a fault, which is oriented in ~NE-SW direction, and a series of ridges that are enclosed within the fault zone (Fig. 2B) are also faulted. A closer look reveals that these faulted ridges preserve ~SE dipping beds (see the yellow window in Fig. 2B).

The abrupt rise of topography in an area that is otherwise flat further suggests faulting. The fluctuations in the sea-level could be argued to have played a role in the formation of subdued topography but such variations over the geological past cannot produce the topography as observed in the region. This

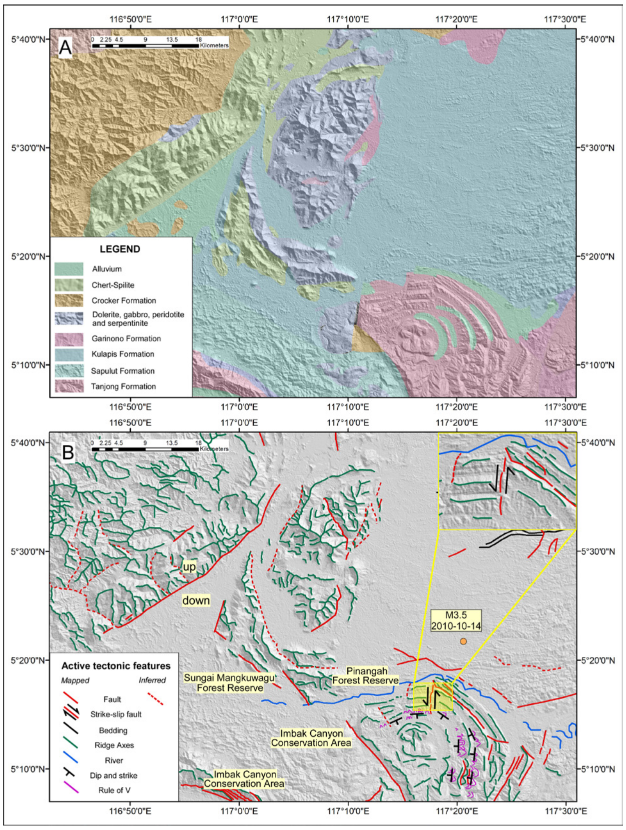

Figure 3: (A) Uninterpreted 30 m SRTM image with geology overlaid on it; (B) Interpreted image shows the mapped geologic and geomorphic features that support the existence of active faults. The truncation of syncline at the western portions is interpreted as a fault. The syncline is exposed as a circular basin with clear evidence for faulting. Small left-lateral strike-slip faults are also mapped (see the yellow rectangular area).

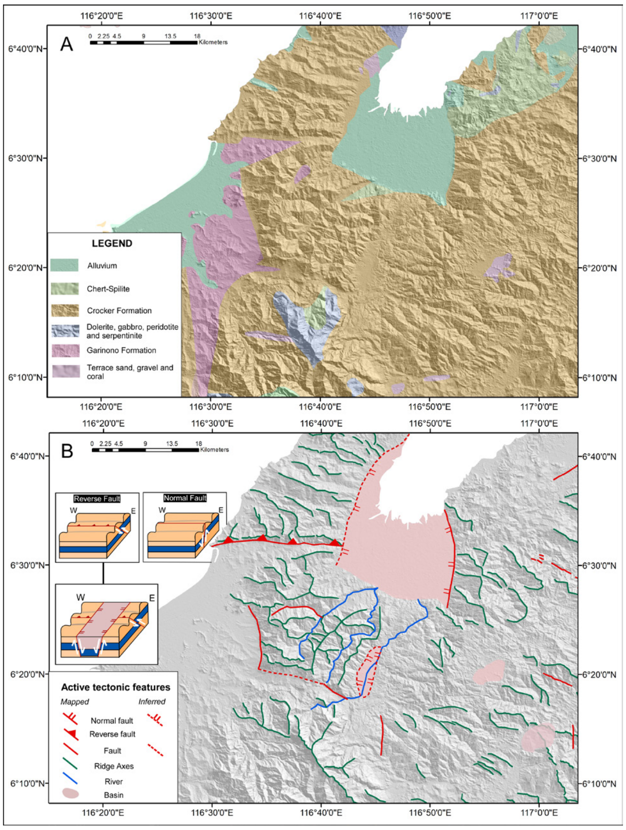

Figure 4: (A) Uninterpreted 30 m SRTM image with geology overlaid on it; (B) Interpreted image shows the mapped geologic and geomorphic features that support the evidence for active faults. The ~E-W reverse faults are truncated by the younger ~N-S trending normal faults, which suggests ~N-S convergence and ~E-W extension.

is because the geomorphic expression of landforms is consistent throughout the region and coincides with the mapped faults and folds (Figs. 2 and 3). We think the entire region is shaped by faulting, and topography is structurally controlled at depth. The mountains are slowly fading from the longitude 117°5′E towards the east, and then the abrupt rise of the ~NE-SW trending ridge is observed (Fig. 2A).

The pattern of discontinuous ridges caught within the fault zone for a total length of ~45 km is consistent with a characteristic fault bend geometry that fits a contractional duplex geometry (Fig. 2B). We are unable to find a clear strike-slip displacement that could be measured and qualified, but we interpret the topographic expression of faulting to be consistent with a fault that has a strike-slip component to it. Therefore, the major fault plane is either dipping ~NW or ~SE, and we have interpreted it as ~SE dipping normal fault with a strike-slip component. This interpretation is based on the topographic expression where upthrown and down-thrown movements are consistent with a normal fault geometry. We named this fault the Pamol Fault, homonym to the nearby city, as we are unaware of any previous references to this fault in the published literature. We have observed and mapped asymmetrical anticlinal structures at the base of the fault zone (Fig. 2B), and these are related to faults, and in good agreement with a fault-bend fold geometry, which suggests oblique extension with strike-slip movement as the ideal condition for the formation of such structures (Fig. 2b).

On the NE side, the fault runs into the Sulu Sea, where its continuation cannot be traced based on satellite data. However, the south-western termination of the fault seems to root at the Crocker fault zone (Fig. 4; Shah 2016; Wang et. al., 2017), which could mean that the fault is a major fault with more than 250 km in length. The fault zone is discontinuous and often segmented (Figs. 2–4), which is suggested by the mapping of the fault zone in the southwest (Fig. 3B). A clear truncation of the ridge crests is observed where mountains suddenly disappear in a valley that is part of the down-thrown block across the fault zone. The fault is consistent with ~SE dipping normal fault geometry, and this portion of the fault zone seems purely normal with no indication of strike-slip. However, we have mapped clear evidence of left-lateral strike-slip where a portion of the syncline is offset by a small ~N-S trending fault (Fig. 3B, see the yellow rectangular area). The ~NW-SE trending fault zone is the major fault (Fig. 3B) where some of the peculiarly shaped basins known as "circular basins' exist and these are cut across by the fault. The circular basin preserves triangular facets that show the dip direction of the beds and it suggests a synclinal geometry for the basin. We have interpreted the structure as a normal fault that dips ~SW. This fault stops at the Pamol Fault, which indicates that the two faults interact and could be related to each other.

The northern portion of NW Borneo has a near rectangular bay area, which is bounded by mountains on three sides (Fig. 4A and 4B). We have mapped an ~E-W trending fault that could either be dipping north or south, and we interpret this fault as a north dipping reverse fault. It suddenly truncates the onshore extension of the basin area, which we have interpreted as a normal fault (Fig. 4B). We think the basin is bounded on two sides by normal faults, and we have mapped one that is shown in solid, and the other as inferred because the evidence of faulting is not clear.

The abrupt termination of the mountain range and opening of the basin within the mountains is a reflection of faulting, which was confirmed by our geomorphological mapping where ~N-S trending active faults bound the basin in east and west (Fig. 4B). The structural configuration and geometry of the basin could be possible with two normal faults that terminate in the south. The existence of ~E-W to ~NW-SE trending fold and thrust faults on the eastern and western portions of the basin (Fig. 4B) suggests that these faults are older and the bay region has formed recently. We interpret that the older faults are dominantly reverse faults, and are later cut by younger ~N-S trending normal faults (Fig. 4B). This indicates that older faults used to continue throughout the region before the bay was formed, and now those faults are cut by the normal faults of the bay region.

5. Discussion

We have mapped a variety of previously unreported active geomorphic features and fault scraps in northern Borneo, and also refined the previously known structures (Figs. 2–4). The presence of the Pamol Fault that possibly extends for >250 km and merges with the Crocker fault zone suggests that deformation in the region is tectonically controlled because gravity alone cannot explain the scale, extent, and morphology of the fault system that we have shown here (Figs. 2–4). Our mapping suggests that the fault is possibly sinistral in the northeastern portions (Fig. 2B), which is shown by the sudden occurrence of ridges in the otherwise low lying regions. We relate this to the restraining bend geometry of the major normal fault with a sinistral component (Fig. 2B). The overall morphology of the entire fault zone resembles the geometry of a major normal fault that dips ~SE and has possibly a strong strike-slip component in the northeast, which is not observable in the southwest and along the track where it eventually merges with the Crocker fault zone.

Alternatively, if we consider the Pamol Fault as a SE dipping reverse fault, as has been mapped in some of the earlier works (JMG, 2012; Wang et al., 2016; Mustafar et al., 2017), then the hanging wall portions should be up, and not down (Fig. 2B). The geomorphic expression of faulting is consistent with up-thrown blocks on the NW and down-thrown portions on the SE of the fault.

Another possibility, which seems consistent with the geomorphic expression, is that the fault is a NW dipping reverse fault with a sinistral strike-slip component. Yet, the NW Borneo region is experiencing crustal extension, which has been suggested by a number of normal fault-related earthquakes in the past and further supported by the field and earthquake moment tensor data (Shah, 2016).

We therefore interpret the Pamol Fault as the SE dipping normal fault. This fault could be related to the major strike-slip fault system that was anticipated earlier and runs through the spine of Borneo Island (Shah et al., 2018; Navakanesh et al., 2020). We have also mapped the ~NW-SE trending normal fault that has ruptured a synclinal circular basin (Balaguru et al., 2003; Chang et al., 2019) and it merges with the Pamol fault at the north (Fig. 3B). We think there is a broad fault zone between the synclinal circular basin and regions north of Pinangah Forest Reserve (Fig. 3B) but the evidence is subtle, and work on the ground is needed.

The earthquake centroid moment tensor data (Navakanesh et al., 2019; Navakanesh et al., 2020) show one earthquake event closer to the Pamol fault, and that has occurred on a strike-slip with either ~N-S strike or ~E-W. The ~N-S trend is closer to the fault, and therefore it appears to have ruptured a sinistral strike-slip fault at 12 km depth, which is consistent with the local origin of the earthquake. This further suggests that the mapped fault could be an oblique fault with a strike-slip component in the northeast and dominantly dip-slip in the southwest. The Pamol Fault is a major fault that could be >250 km long, and the examination of available earthquake centroid moment tensor data suggests that Borneo is dominantly undergoing normal and strike-slip faulting, and our work shows that the entire region is undergoing transtension.

6. Conclusions

Our geomorphological mapping has demonstrated that active faults exist in NW Borneo, which are mainly related to oblique crustal extension that is accommodated by the formation of normal and strike-slip faults. The evidence for active faulting (Figs. 2–4) is widespread, and broadly the Pamol fault zone belongs to a family of faults that exist in northern Borneo, which is related to the ongoing oblique crustal extension on the island. The scale, extent, and youthfulness of landforms suggest that tectonics is driving the ongoing deformation of Borneo, which could also be facilitated by gravity-induced deformation but gravity alone cannot be the major source of active deformation in the region.

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