Is the Active Deformation in NW Borneo Tectonically-Driven or Gravity-Induced?

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1. Introduction

The cause of active deformation of NW Borneo is a controversial topic. While some studies have shown evidence for active plate convergence along at the NW Borneo-Palawan Trough (Hutchison, 2010), others consider that evidence for plate convergence is lacking, and argue for episodes of crustal extension as the cause of Neogene deformation. For example, Hall (2013) suggests that the Borneo-Palawan Trough lacks features associated with a typical subduction zone, and therefore it is not a subduction-related trench, and instead interprets the structure as gravity-driven with a contribution from deep crustal movement. This raises questions on what is causing active deformation in the region, gravity or tectonics, and that is the focus of our study.

The interaction of the Indo-Australian, Sunda, and Philippine Sea plates creates a buzz of seismicity that encloses the Island of Borneo and confirms the active plate tectonic processes in the neighborhood. A closer look at the centroid moment tensor data of the earthquake events in NE Borneo shows that the regional tectonic deformation is accommodated by normal, thrust, and strike-slip faults, which could very well be related to crustal deformation related to plate tectonic processes, or alternatively, a product of local topographic effects and gravity-induced faulting. The answer to this problem is not a straightforward yes or no, and instead requires a comprehensive examination of various data such as seismological, geomorphological, geological, and geodetic.

On the regional scale, the tectonic strain is usually released by the occurrence of medium to large magnitude earthquakes (Fig. 1A). However, the occasional occurrence and sparse distribution of earthquakes on the Island of Borneo means that the region is not as active as the neighboring regions (e.g. Sapin et al., 2009). The present tectonic map of the region places Borneo as part of the Eurasian plate, and more specifically the Sunda plate (Fig. 1A), which seems to be tectonically stable when only earthquakes are used as the criteria of active tectonism. Therefore, the cause of active deformation in this region remains debated with two broader outlooks: either driven by gravity (Hazebroek and Tan, 1993; Hall, 2013), or by gravity and far-field compression (Ingram et al, 2004; Sapin et al., 2013). Here we review all of the major published works on the active deformation of NW Borneo and re-evaluate the structural data with the main focus on the causes of active deformation in the region. The field observations are supplemented with the centroid moment tensor data to support the new synthesis, which is presented below.

2. Active tectonics in NW Borneo

The active deformation in NW Borneo has been discussed extensively (e.g. Ingram et al., 2004; Mathew et al., 2016; Shah, 2016; Tongkul, 2016; Tongkul, 2017; Wang et al., 2017; Shah et al., 2018, Wu et al, 2020), and the largest earthquake in the recorded history occurred in June 2015 when a normal fault system ruptured in Sabah (Fig. 1D). The cause of active faulting in the region is broadly related to either non-tectonic (gravity-driven) or gravity plus tectonic causes (e.g. Ingram et al., 2004; Hesse et al., 2009; Sapin et al., 2013; Wang et al., 2017, Shah et al., 2018, Wu et al., 2020). These interpretations emerge from the fact that earthquake distribution on the Island of Borneo is very sparse and mostly concentrated in the far north (Fig. 1A), and the active structures that are mapped in the region are usually related to typical gravity-driven local deformation and not tectonics (e.g. Hazebroek and Tan, 1993). But there are many problems in a solely gravity-driven active deformation model, which are discussed below, and are supported by the mapping of new geomorphic evidence for active tectonic structures.

3. Methodology

The data on previously published structural maps are compiled (Fig. 1) from various sources that include Wang et al. (2016), Shah (2016), Wang et al., (2017), Mustafar et al. (2017), and JMG (Malaysian Government Agency), and references therein. These are plotted on the digital elevation model (DEM) derived image to show the extent and type of faulting

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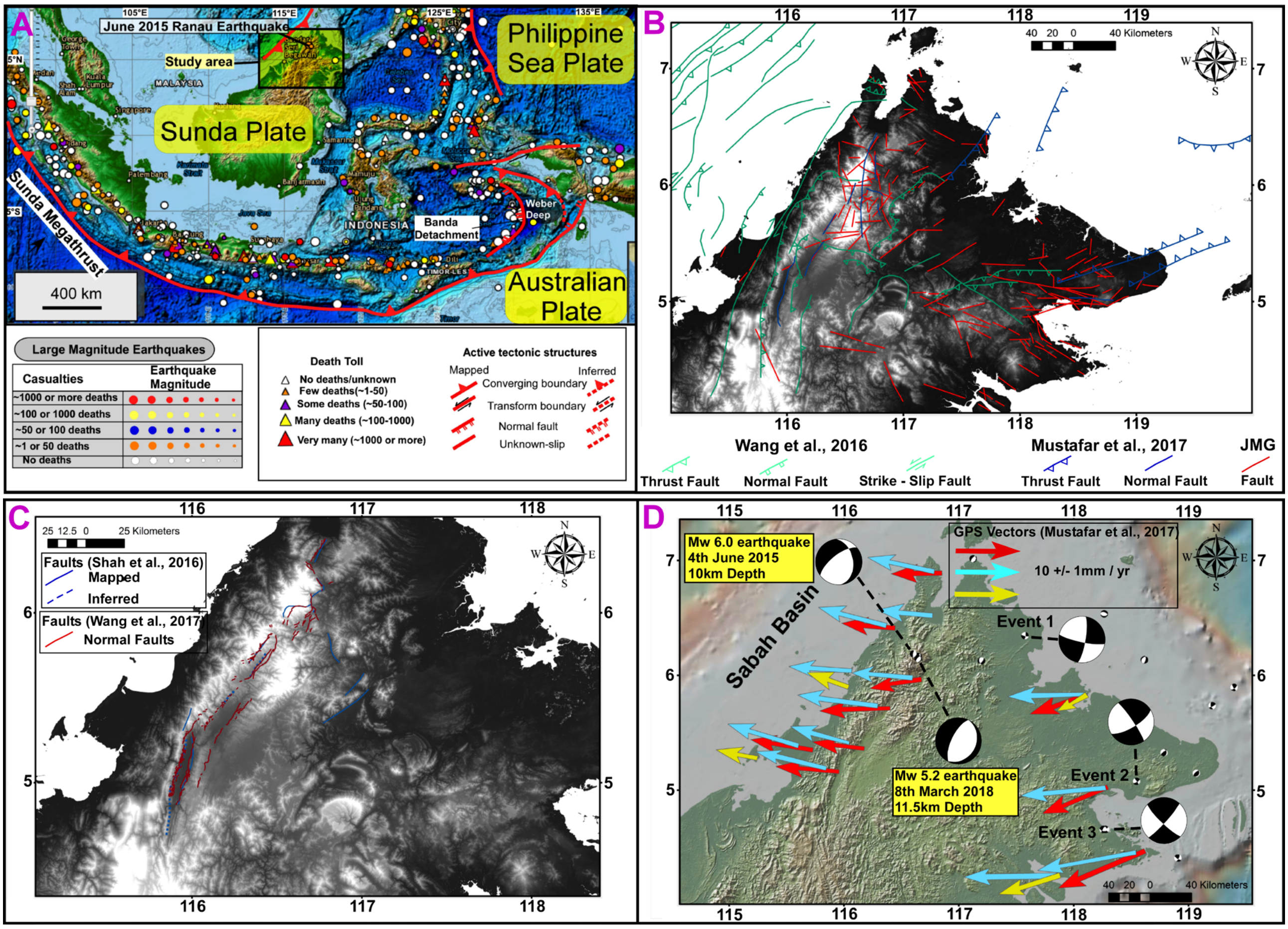

Figure 1: (A) Regional tectonic map of SE Asia that mainly shows the active tectonic plate boundary faults systems. The color filled circles show significant earthquakes that have caused damage to life and property (modified after Shah et al., 2018). (B) Digital elevation model (DEM) derived image with previously mapped fault data that are sourced from Wang et al. (2016), Mustafar et al. (2017) and JMG (Malaysian Government Agency). (C) The presence of active faults in Sabah (after Shah, 2016 and Wang et al., 2017). (D) The GPS vectors show a NW to W directed present day crustal movement, which suggests oblique extension on Crocker fault system (GPS data after Mustafar et al., 2017).

(Fig. 1B,C) (Shah and Malik, 2017). We have also collected data (Fig. 2) on the exact position of the West Baram Line, known as Tinjar Line onshore (Cullen, 2014), which has been mapped and interpreted either as a transform boundary, a fault, or a structural discontinuity with unknown slip. The exact location is also a controversial topic (Fig. 2). The GPS vectors (Mustafar et al., 2017) are plotted on the satellite data using the open-source GeoMap App application. The centroid moment tensor solutions of the available earthquakes are extracted from the GeoMap App and examined to find a possible correlation with the faults that are mapped on the images (Fig. 1D). This involved recording the strike, dip, depth, and rake of each event. We only included earthquakes that originated at < 50 km depth because we focus on crustal deformation only. Fieldwork was conducted in parts of Sabah, Malaysia, to map evidence of active faulting (details in Navakanesh et al., 2019).

4. Results and Interpretations

The investigation of previously published structural maps of NW Borneo (Fig. 1A–C) shows that a number of faults have been mapped but the data in Wang et al. (2017) and Shah et al. (2016, 2018) fit well with the field (Fig. 3) and seismological data. The earthquake centroid moment tensor data show the dominance of normal and strike-slip faulting in the region (Fig. 2), with a normal faulting mechanism in Sabah and adjacent regions (Fig. 1D). Note the occurrence of normal faults in the northern tip of Borneo, which suggests either ~SE or ~NW dipping faults. Both these possibilities exist, which is supported by our geomorphic and field evidence, and the ~NW dipping normal fault system that ruptured at ~12 km depth on 4th June 2015 and on 8th March 2018 (Shah et al., 2018; Navakanesh et al., 2019), resembles that fault that we have mapped in the field (Fig. 3).

A number of strike-slip earthquake events are also very distinct in the region, and particularly those that have occurred in eastern Borneo (Fig. 1D). The strike-slip earthquake (Fig. 1D, event 1) could have

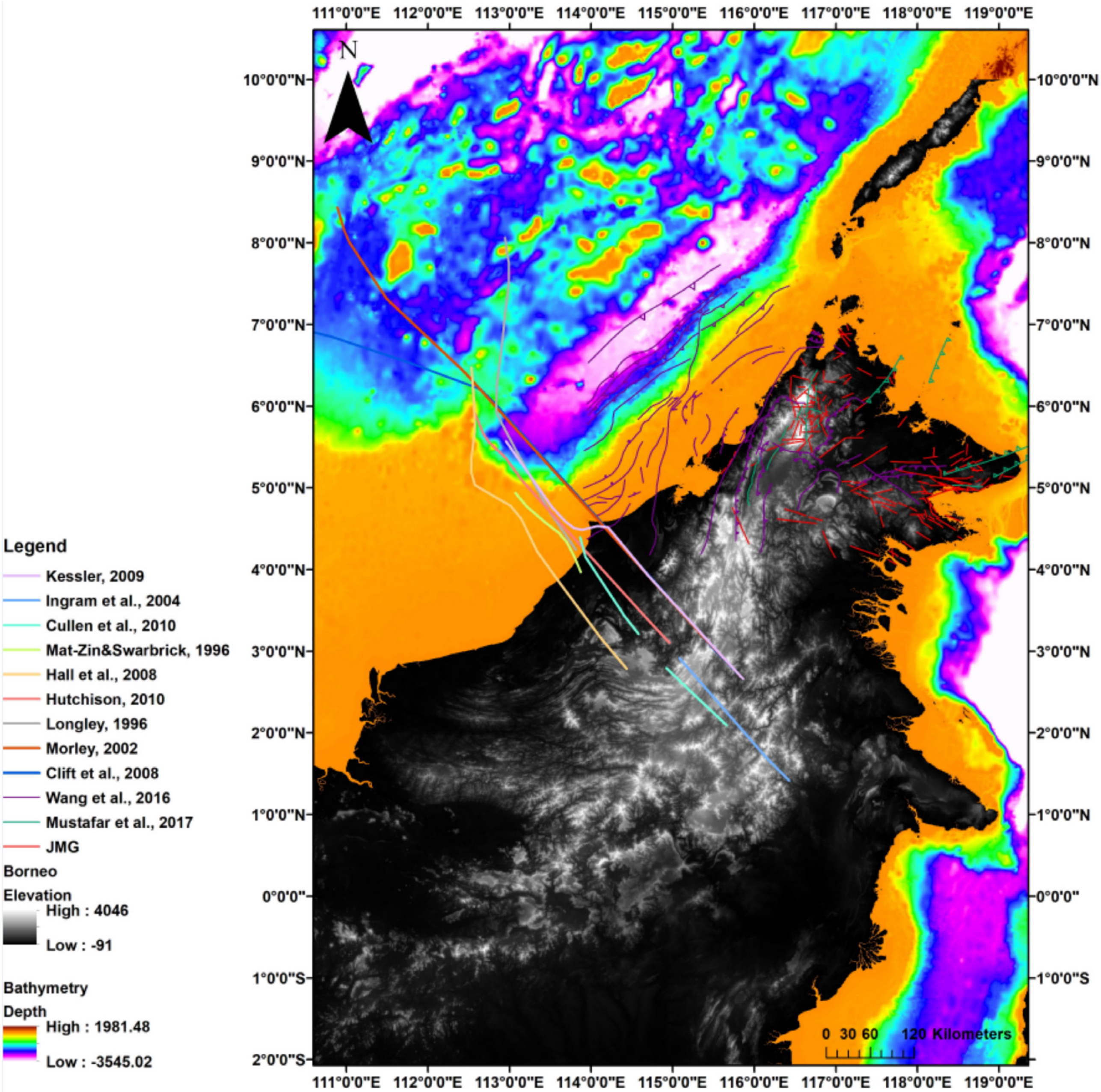

Figure 2: The ongoing active deformation of NW Borneo region is controversial, and this is also reflected in the mapping of major structures. For example the West Baram Line (known as Tinjar Line onshore) is either considered a transform boundary, a fault, or a structural discontinuity with unknown slip. And the exact location also remains a controversial topic.

occurred following left-lateral strike-slip movement along a ~NE-SW trending fault or by dextral strike-slip movement on a ~E-W trending fault. The existence of a similar fault was shown by Navakanesh et al. (2019) and that fits the left-lateral strike-slip faulting (Fig. 1D, event 1). The oblique strike-slip earthquakes that are recorded in eastern Borneo (Fig. 1D, events 2 and 3) show either dextral or sinistral faulting. The topographic expression of active strike-slip faulting in Borneo was shown by Shah et al. (2018) and the centroid moment tensor data clearly back such type of faulting in the region. This suggests that the occurrence of active strike-slip faulting in Borneo is perhaps common. Details on this faulting could be obtained through paleoseismological work on some of the major faults.

The pattern of earthquakes and the previously published structural data show active deformation in NW Borneo, and field data shows the dominance of normal faulting (Wang et al., 2017; Navakanesh et al., 2019). The field data are collected after the June 2015 event but the evidence for co-seismic surface rupturing was not observed, which suggests blind normal faulting. During our fieldwork, we have mapped old fault systems that show similar structural parameters (Fig. 2), which include the fault dip angle and direction. For example, a number of normal faults are mapped with both NE and SW dip directions (Fig. 2), and the faults are not observed to have ruptured any of the Holocene deposits. Therefore, the normal

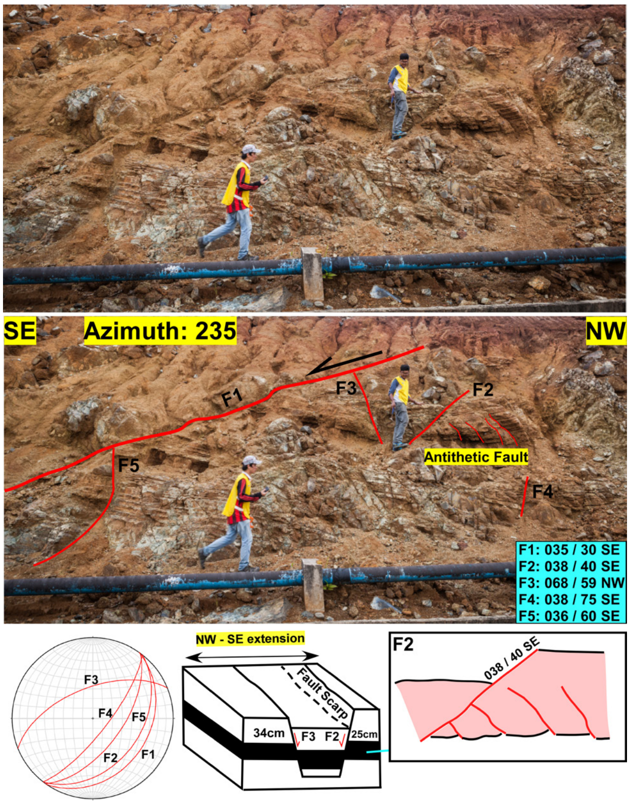

Figure 3: The un-interpreted field photograph is shown at the top, and the Interpreted (bottom) shows the occurrence of NW and SE dipping normal faults in the region. The stereonet plots show the same, and suggest an older normal fault system with NW-SE directed regional extension.

faulting event that struck Sabah in June 2015 was a common occurrence and similar earthquakes should have occurred in the past, as is clearly visible from the bedrock faulting. However, the age of recent activity on these faults is not known, which requires further work on the ground.

5. Discussion and Conclusions

Understanding the cause and occurrence of intraplate earthquakes remains a challenge, particularly in regions that are considered tectonically stable. The notion of this is vigorously debated after the 4th June 2015 earthquake that caused significant damage and loss of life (Wang et al., 2017; Shah et al., 2018; Navakanesh et al., 2019). The geomorphic, geologic, and structural mapping details available from the region have clearly demonstrated that NW Borneo is active. Although the geomorphic analysis indicates the presence of active tectonic fault scarps (Hutchison, 2005; Cullen, 2010), such evidence is not observed in the field because it is usually buried under sediments. The evidence of mapped normal faults that have displaced the basement rocks and show similar structural parameters that were recorded during the June 2015 and March 2018 events (Fig. 1) seems to suggest that older faults have been reactivated. The lack of Holocene earthquake ruptures suggests that faulting is either blind, or the earlier evidence for fault ruptures has been erased in the tropical conditions of the Island. Regionally, the currently occurring direction of extension is ~NW-SE, and it seems that the deformation is controlled at depth by the major strike-slip fault (Shah et al., 2018) that runs through the backbone of the Island. This means that the deformation is a product of oblique convergence, and if that is true, then this part of the Sunda plate is undergoing active extension (Fig. 4). Since the region is apparently not influenced by the nearby subduction systems, this kind of deformation could be related to intra-plate deformation processes or far-off stresses. Alternatively, the active tectonic convergence along the Borneo-Palawan Trench could explain active deformation onshore NW Borneo. However, evidence for subduction is subtle or even not convincing, and Hall (2013) argues against the active tectonic convergence at the trough. We also suggest that Borneo-Palawan trench does not resemble a typical subduction zone and its abrupt termination at the southwest questions the association with a tectonic trench. It is more like a crustal extensional feature that was later filled with sediments that are undergoing active deformation induced by gravity, and far-field tectonics.

The cause of active deformation in this region could be attributed to gravitational causes that require a subsurface stratum onto which the sliding is possible, and previous work has suggested that a pressured shale lithology at depth could provide suitable conditions to make sliding possible (Sandal, 1996; Sapin et al., 2013). And in NW Borneo, the Setap shale, which sits at the base, is a good candidate to act as a décollement onto which rocks can glide like a large-scale landslide. However, if this is true, structural and geometrical constraints apply and one would expect a more or less systematic orientation of structures that would be expected from this type of deformation model. Figure 4A illustrates the gravity-driven deformation model, and such a model would predict a ~NE-SW strike of normal faults in onshore regions, and similar but reverse faults at the toe. It also requires strike-slip faults at both sides as bounding structures that limit the deformation of the Baram delta (Tjia, 2003). However, large-scale strike-slip faults have not been mapped in the region. The only structures that are mapped are the largely undifferentiated West Baram Line (Tinjar line), which could be a good fit (Fig. 2) but presently would be expected to follow a sinistral sense of movement, which needs to be tested. However, the gravity-driven deformation model cannot explain the deformation within central and eastern

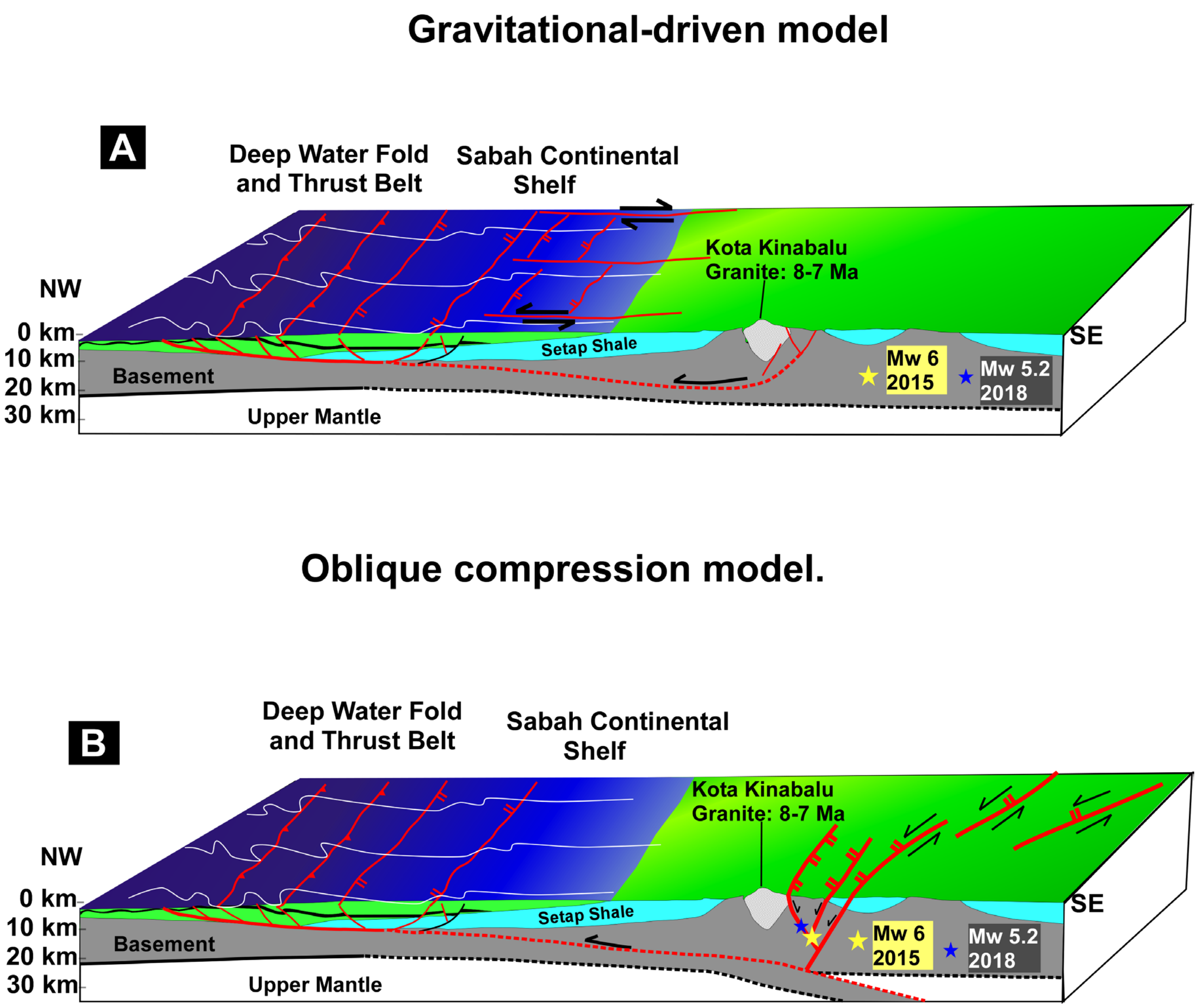

Figure 4: (A) Gravitational-driven model. The model illustrates gravity alone could not explain the deformation in NW Borneo. The conceptual idea here is the strike slip systems must have initiated transtensional settings along the Sabah continental shelf. At depths of 10 km, the gravitational deformational seems ineffective without an active influence of additional forces that are usually tectonic in origin. (B) The oblique compression model of Shah et al (2018) shows the occurrence of a major strike slip system along the backbone of Borneo Island, which could be controlling the additional deformation that gravity alone cannot explain.

Borneo, where active deformation is ongoing (Shah et al., 2018). Therefore, we argue that strike-slip fault-related events recorded in Borneo are related to active deformation onshore, and suggest that the Island is slowly accumulating strain that could be related to far-field tectonic stresses and not just sliding under the influence of gravity (Shah et al., 2018). Finally, the depth, scale, extent, and type of faulting in Borneo are challenging and cannot be simply explained by just gravity-driven deformation models. Therefore, we propose that gravity-driven deformation and tectonic stresses work together to explain the deformation in Borneo. Similar conclusions are drawn by some of the past studies where the amount of shortening and extension within NW Borneo has been interpreted to understand and quantify the deformation related to gravity-driven and far-field tectonic processes in northern Borneo since the late Pliocene (Hesse et al., 2009; King et al., 2010). The recent data have demonstrated that the amount of shortening within the NW Borneo deep-water fold belt cannot be fully explained by just gravity-driven shortening, and it most likely involves tectonic shortening (Wu et al., 2020).

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