Bulletin of the Geological Society of Malaysia, Volume 64, December 2017, pp. 27 – 36

Active tectonics in Sabah – seismicity and active faults

Felix Tongkul

Natural Disaster Research Centre (NDRC),
Universiti Malaysia Sabah,
88400, Kota Kinabalu, Sabah
Email address: ftongkul@ums.edu.my

Abstract: The location of Sabah near the boundaries of three major tectonic plates, the Eurasian, India-Australia and Philippine-Pacific plates, makes it prone to seismic activities. Sabah is currently under a WNW-ESE compressive stress regime due to the effect of plate movements as the Philippine-Pacific plate move westward at the rate of about 10 cm/year against the southeast moving Eurasian plate at the rate of about 5 cm/year. The WNW-ESE compression is being accommodated by NE-SW trending active thrust faults and NW-SE trending active strike-slip faults present all over Sabah. Evidence of active faults based on geomorphological features, such as linear structures associated with triangular facets, stream offsets, mud volcanoes and hot springs are widespread in Sabah.The WNW-ESE compression resulted in regional folding or warping of the upper crust to produce an uplifted belt trending NE-SW in Western Sabah, currently occupied by the Crocker-Trusmadi Range. The warping and uplift of the upper crust is thought to be driving extensional tectonics, marked by the presence of NE-SW trending active normal faults along the crest and flanks of the Crocker-Trusmadi Range anticlinorium. At least six elongate Quaternary graben-like basins (Tenom, Keningau, Tambunan, Ranau, Timbua and Marak-Parak) occur along the crest of the anticlinorium.

Keywords: compressive tectonics, extensional tectonics, seismicity, active faults, Sabah

INTRODUCTION

Sabah has long been known as the most tectonically active area in Malaysia due to its relative proximity to the major plate boundary faults in the Philippines and Sulawesi active subduction zones. The June 5, 2015 magnitude 6 earthquake which jolted the town of Ranau and Kundasang spectacularly reinforced active tectonics in Sabah (Tongkul, 2016). Earthquake records from Sabah shows seismic activities since 1897 (Lim, 1985 & 1986; Wilford, 1967; Leyu *et al*., 1985) generated by intra-plate active faults. Earthquake focal mechanism solutions provided by USGS indicate that the intra-plate earthquakes were related to both extensional and compressional active faults. For example, the magnitude 6 Ranau earthquake which occurred on June 5 2015 was associated with a normal fault. Similarly a magnitude 5.1 earthquake in 1991 south of Ranau was also associated with a normal fault. The 1976 magnitude 6.2 Lahad Datu earthquake was associated with a strike-slip fault, whereas the 1984 magnitude 5.7 Tabin earthquake was associated with thrust faults.

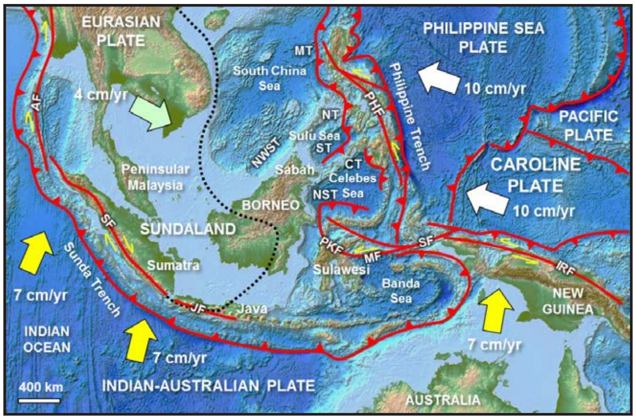

Figure 1: Tectonic setting of Sabah showing major plate movements. The Philippine-Caroline-West Pacific Plate moving relatively faster towards the west. MT: Manila Trench, NT: Negros Trench, ST: Sulu Trench, CT: Cotabato Trench, NST: North Sulawesi Trench, NWST: NW Sabah Trough, PHF: Philippine Fault, PKF: Palu-Koro Fault, MF: Matano Fault, SF: Sorong Fault, IRF: Irian Fault, AF: Andaman Fault, SF: Sumatra Fault, JF: Java Fault.

Although the seismic activities clearly points to the presence of active faults, the status of these active faults are yet to be clearly ascertained in Sabah. The presence of active normal faults in a compressive region is also intriguing. Is there field evidence to support the extensional model in Sabah? How do we reconcile the presence of both compressional and extensional regime in the same area? This paper provides some insights into these important questions based on recent study utilizing remotely-sensed images and field observations.

TECTONIC SETTING OF SABAH

Sabah is located close to the most seismically active plate boundaries between the Indian-Australian Plate and Eurasian Plate in the west and between Philippine Plate in the east (Figure 1). GPS measurements indicate that the three major plates are converging at each other at different directions and rates (Mitchel *et al.*, 2001; Simons *et al.*, 2007). The Eurasian Plate, that includes Sundaland and South China Sea Basin (stretched continental margin) is moving southeastward at a rate of about 4 cm/yr. The Indian-Australian Plate is moving northerly at a rate of about 7 cm/yr whereas the Philippine Sea-Pacific Plate is at about 10 cm/yr. The northward movement of the Indian-Australian Plate is associated with N-S spreading of the sea floor in the

Antarctic Ocean since about 50 million years ago, whereas the westward movement of the Pacific Plate is related to the E-W spreading of sea floor in the Pacific Ocean since about 42 million years ago. The interactions of the three tectonic plates are associated with active subduction zones and strike-slip faults. The oblique northward convergence of the Indian-Australian Plate against the Sundaland is marked by the Sunda Trench subduction zone and Java-Sumatra-Andaman dextral strike-slip fault. The oblique westward convergence of the Philippine Sea-Pacific Plate against the Sundaland and Indian-Australian Plate is marked by the active Philippines-Sulawesi-Irian Jaya Mobile Belt. This mobile belt is bounded by the Manila-Negros-Cotabato-North Sulawesi Trench subduction zones to the west and the Philippines Trench subduction zone to the east. The sinistral Philippines and Irian strike-slip fault occurs in between the subduction zones. In this region, the faster moving Pacific-Philippine Sea Plate bends the Sunda Trench westward along the Sorong-Matano-Palu-Koro sinistral strike-slip faults.

Sabah, sitting on the semi-stable South China Sea Basin, is to a certain extent influenced by the active mobile belts in Sulawesi and Philippines. The active Sulu Trench subduction zone appears to continue into East Sabah. Similarly the active Palu-Koro Fault in Sulawesi appears to continue into East Borneo. GPS measurement of movement across the Palu-Koro fault showed 3.4 cm/yr sinistral strike-slip movement (Walpersdorf *et al*., 1998). In South China Sea, the NW Borneo Trough which was probably once associated with subduction zone is not seismically active. Active thrust faults found along the trough may mostly be associated with sedimentary loading and slumping or due to crustal shortening.

REGIONAL SEISMICITY AND PLATE MOVEMENTS

Sabah is affected by both regional and local earthquakes. Significant earthquakes from the Sulu and Celebes seas are periodically felt as slight tremors in Sabah. The USGS earthquake database shows hundreds of earthquakes ranging from shallow to deep. The earthquakes provide important clues to past and current plate movements surrounding Sabah.

Deep earthquakes (more than 300 km depth) associated with the Philippine Plate subducting slab can be clearly seen on the eastern part of Celebes Sea area (Figure 2). The NNE-SSW trending distribution of the deep earthquakes in Celebes Sea shows that the slab is being subducted approximately westward towards Sabah under the Celebes Sea and Sulu Sea along the Philippine Trench and Sangihe Trench. The subducting slab appears to be truncated by the Sorong Fault to the South and the Philippine Fault System to the North.

The distribution of shallow earthquakes (less than 70 km depth) of magnitude less than 5 show the Celebes Sea oceanic lithosphere subducting southward under North Sulawesi along the North Sulawesi Trench and eastward under South Philippines along the Cotabato Trench (Figure 3). Similarly the Sulu Sea oceanic lithosphere is subducting eastward under Central Philippine along the Negros and Sulu trenches. The South China oceanic lithosphere is subducting under North Philippines along the Manila Trench. In East Sabah and Northeast Kalimantan the earthquakes appear to be associated with intra-plate thrust faults.

Based on the earthquake data it can be inferred that the stress generated by the deep westward subducting slab of the Philippine Sea is being absorbed by shallow eastward and southward subduction of the Celebes Sea and Sulu Sea plates. In Sabah the stress appears to be absorbed by active thrust faults resulting in shortening and gradual uplift of Sabah (Figure 4). The thrust faults along the NW Borneo Trough and SE Borneo Trough probably marks the western and eastern boundary of the Sabah stress field.

Further analysis of the stress directions derived from the regional earthquakes around Sabah show two main stress directions domains, an E-W stress direction onshore Sabah and approximately NE-SW direction offshore Sabah (Figure

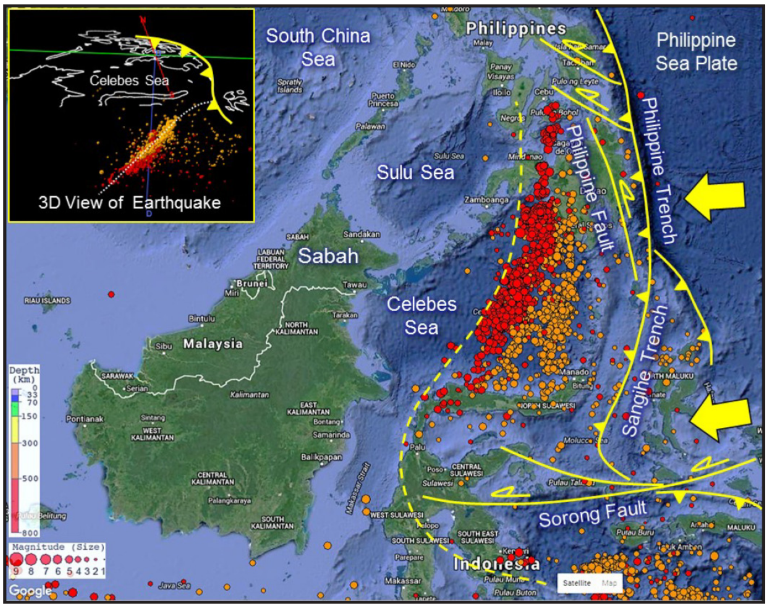

Figure 2: The distribution of deep earthquake with more than 300 km depth associated with subducting slab of the Philippine Sea Plate under the Celebes Sea and Sulu Sea towards the WNW (see 3D View). The NE-SW trending yellow dashed line indicating the western edge of the subducted slab bends to the southeast in Sulawesi. The subducted slab appears to be bounded by sinistral strike-slip faults to the north (Philippine Fault) and south (Sorong Fault). Earthquake data extracted form USGS database.

5). The two stress directions appears to be separated by a fault trending NE-SW along the coast of SE Sabah. The NE-SW stress affects mostly NE Kalimantan. The different stress directions possibly indicate the presence of a microplate boundary associated with a dextral strike-slip fault.

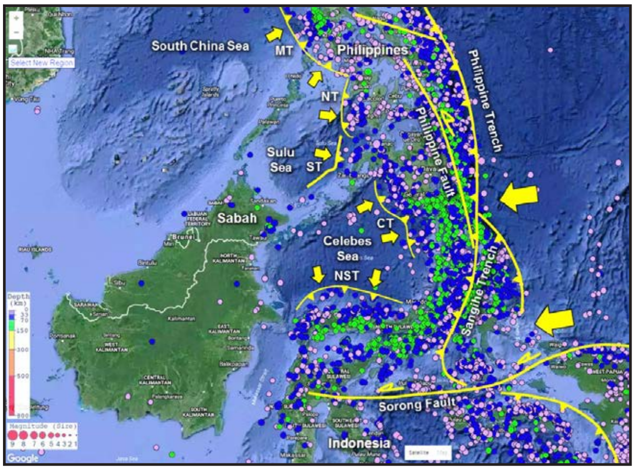

Figure 3: The distribution of shallow earthquake (magnitude more than 5) with less than 120 km depth associated with subducting slab of the Celebes Sea, Sulu Sea and South China Sea dipping southward under Sulawesi (NST: North Sulawesi Trench) and eastward under the Philippines (MT: Manila Trench, NT: Negros Trench, ST: Sulu Trench and CT:Cotabato Trench). In East Sabah and Northeast Kalimantan the earthquakes are produced by thrust and strike-slip faults. Earthquake data extracted from USGS database.

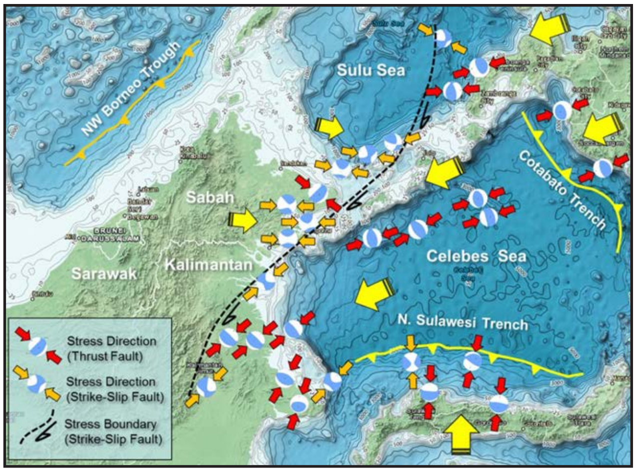

Figure 5: The distribution of stress direction based on focal mechanisms in East Sabah and surrounding areas. The different stress directions in SE Sabah (West direction) and Celebes Sea (Southwest direction) possibly indicate the presence of a microplate boundary associated with a dextral strike-slip fault. The focal mechanism is extracted from USGS database.

LOCAL SEISMICITY AND STRESS DIRECTION IN SABAH

During the period from 1900 to September 2016, based on the USGS and IRIS earthquake database, about 65 local light to moderate (magnitude larger than 3) earthquakes were recorded onshore Sabah or within the waters of Sabah. The small number of earthquakes is due partly to

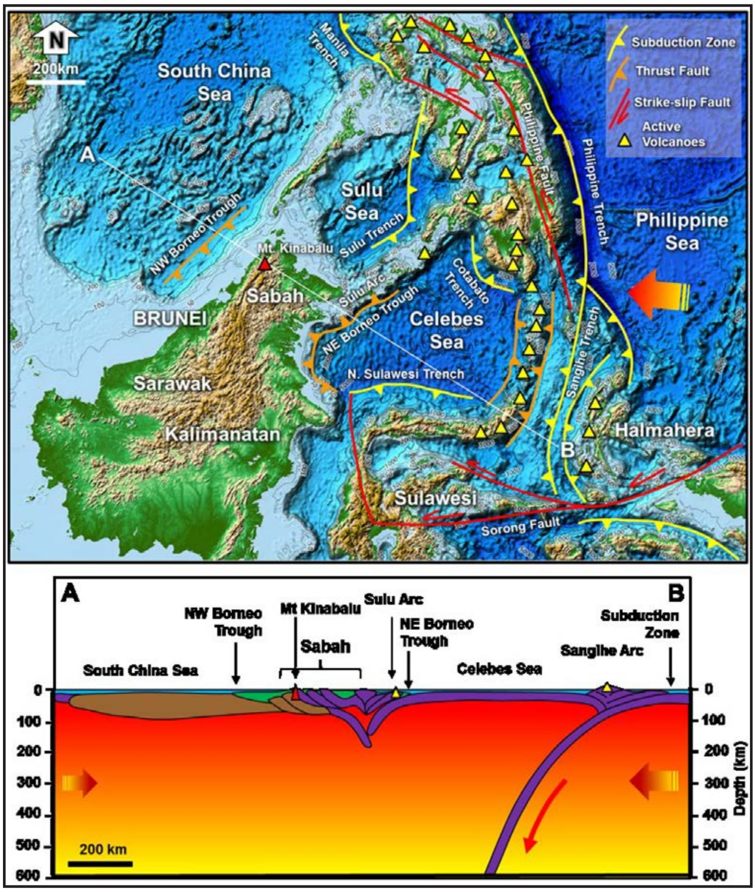

Figure 4: Summary of active plate movements east of Sabah. The Philippine Sea Plate subducting westward under the Sulu-Celebes Sea area producing WNW-ESE compressional stress in Sabah.

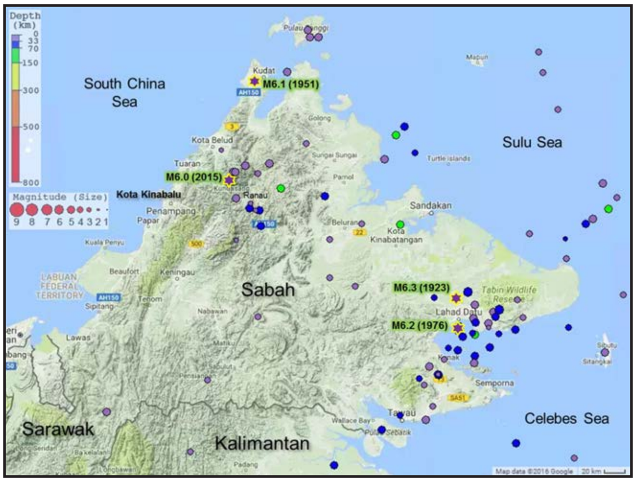

Figure 6: Earthquake distribution in Sabah (1973-2016) extracted from IRIS earthquake database mostly showing shallow depth (less than 70 km). The yellow star shows the location of earthquake with magnitude 6 and above extracted from USGS database.

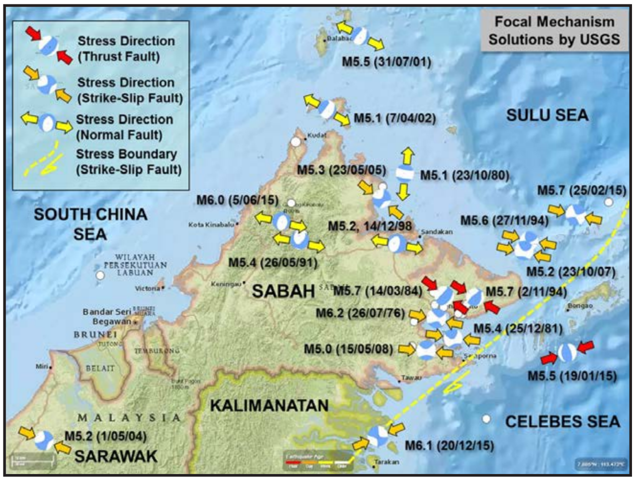

Figure 7: Stress distribution in Sabah based on focal mechanism solutions showing the presence of compressional and extensional stress regime. The normal faults occurs in north, northeast and west Sabah whereas the thrust and strike-slip faults occur in southeast Sabah. The focal mechanism extracted from USGS database.

the detection limit of older seismographs in Sabah. Since the establishment of new seismographs in Sabah in 2009 more micro earthquakes has been recorded in Sabah. For example during 2015 alone, the Metorological Department of Malaysia recorded 155 small earthquakes (magnitude larger than 2) in Sabah. Most of the earthquakes in Sabah have magnitude less than 5. The USGS earthquake database, which provides a more longer coverage period, recorded only 4 earthquakes with magnitude 6 and above, such as the 2015 Ranau earthquake, 1976 Lahad Datu earthquake, 1951 Kudat earthquake and 1923 Lahad Datu Earthquake (Figure 6). The epicenters of the earthquakes are concentrated on the east coast of Sabah, around the Lahad Datu-Kunak area, and around the Kundasang-Ranau area. The earthquakes mainly occurred at shallow depths. The earthquake has caused moderate damage to areas in Ranau and Lahad Datu (Tjia, 1978; Lim, 1976; 1985 & 1986; Lim & Godwin, 1992; Tongkul, 1992 & 2016).

Limited earthquake focal mechanism solutions provided by the USGS show both compressional stress regimes (thrust faults and strike-slip faults) and extensional stress regimes (normal faults) to be responsible for the local earthquakes in Sabah (Figure 7). The compressional stress regimes are mostly recorded in southeast Sabah, whereas the extensional regimes are mostly recorded in west and north Sabah. The compressional and extensional stress directions are mostly oriented WNW-ESE.

REGIONAL STRUCTURES OF SABAH

Sabah is comprised mainly of sedimentary and igneous rocks with minor occurrences of metamorphic rocks ranging in age from probable Triassic to Pliocene (JMG, 1985; Tongkul, 1991). The Mesozoic ophiolitic basement rock represents the oldest rock group, comprising igneous, metamorphic and sedimentary rocks. The ophiolitic rocks are mostly found in Lahad Datu, Telupid, Ranau, Kota Marudu and Banggi Island (Figure 8). Lying unconformably on top of the basement rock are Paleogene or pre-Neogene sedimentary rocks comprising mainly of sandstone, mudstone and minor occurrences of limestone, found all over Sabah. Neogene chaotic deposits or melange deposits lie unconformably on the basement and Paleogene sediments. The deposit is characterised by the occurrence of chaotic mixtures of blocks of a single lithology or different exotic lithologies in a grey or red mud matrix and is confined mostly to east Sabah. Moderately deformed Neogene sedimentary rocks comprising of sandstone, mudstone with minor occurrence of conglomerate, limestone and coal occur mainly in east and southeast Sabah. The rock group occurs as sedimentary depressions, characterised by their circular-

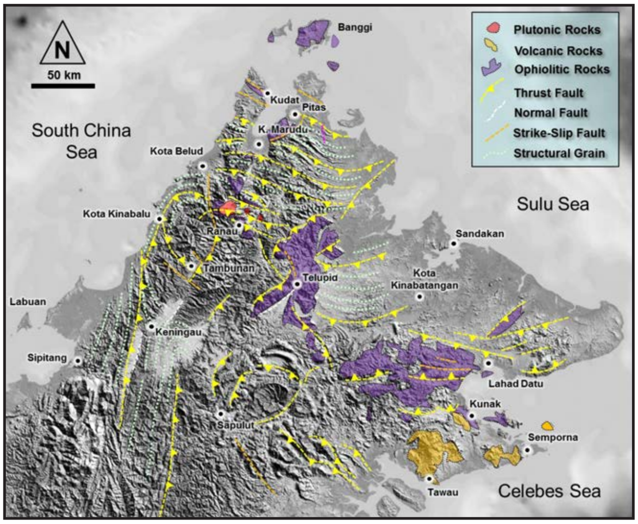

Figure 8: Structural map of Sabah showing the orientation of the main structural grain trending approximately N-S and E-W represented by positive lineaments or elongated ridges. The structural grain follows the fold-thrust belt of the Paleogene Crocker Formation, which dominates the western and northern part of Sabah. The faults shown are mostly ancient faults.

and ellipsoid-shaped basins. Late Neogene plutonic igneous rock intrusions occur in Ranau. The youngest rock group comprises of Quaternary sedimentary rocks and volcanic rocks. The sedimentary rocks comprised of gravel, sand, silt, mud and coral fragments found mostly along the coast of Sabah. The volcanic rocks consist mainly of andesitic and basaltic lava flows.

Regionally, two dominant structural grains, approximately N-S and E-W occur in Sabah. The N-S trending lineaments are found in south and west coast of Sabah whereas the E-W occur in north and central Sabah (Tongkul, 1990). The structural trends are more complicated in the east and southeast parts of Sabah due to the interaction of the two major trends. Other structural trends, for example in the Telupid area, show unconformable relationship, indicating the presence of multiphase deformation (Tongkul, 1997). Associated with the positive lineaments are NW-SE, N-S and NE-SW negative lineaments representing faults or fractures. The nature of some of these faults is uncertain due to lack of control on their displacement. It is possible that some of these faults are still active.

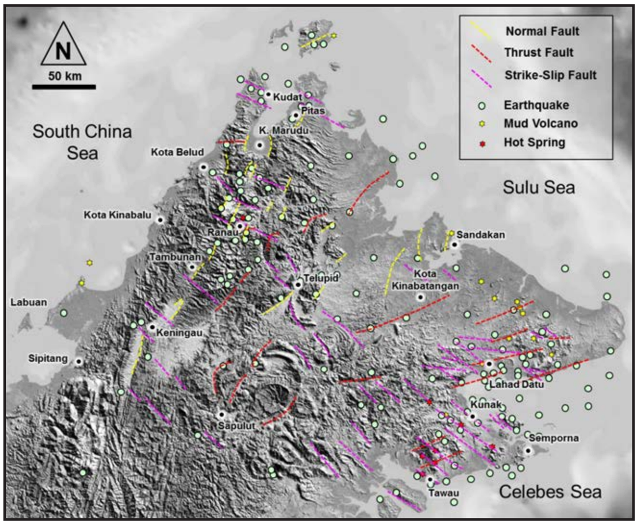

Figure 9: Active and potentially active faults in Sabah based on the presence of negative lineaments, triangular facets, earthquake epicenters, mud volcanoes and hot springs. The earthquakes are based on records provided by MetMalaysia, and from the USGS and IRIS database.

ACTIVE FAULTS IN SABAH

Active faults are defined as linear areas where ground movement occurs systematically and continuously over a large area. Faults are commonly considered to be active if there has been movement observed or evidence of seismic activity during the last 10,000 years (Holocene age). Active faults provide concrete evidence that a region is still undergoing tectonic stress. Active fault identification is a difficult task, especially when ground movements are very small and at very slow rates. Thick vegetation cover coupled with deep weathering profile often conceal ground movements. The occurrence of ground instabilities due to landslides further complicates the identification of active faults.

Mapping of active faults has been carried out in Sabah for the last 10 years by geologists from Universiti Malaysia Sabah (UMS) and the Minerals and Geoscience Department (JMG) with limited results (Tongkul & Omang, 2010; JMG, 2006 & 2008). The latest study on active faults by UMS in collaboration with other public universities (UM, UKM, UiTM, UCSI, UTM) and government agencies (JMG, MetMalaysia, ARSM, JKR) using high resolution radar images (IFSAR) and satellite images coupled with field observations identified several active fault zones in Ranau and Lahad Datu areas (Ismail *et al*., 2015). The active faults will require further investigations, to confirm whether they are indeed active, by monitoring their movements using geodetic techniques such as GPS. To date, monitoring of active faults using GPS in Sabah is still very limited. Only one study was carried out by the Department of Survey and Mapping (JUPEM) in 2010 to monitor the active faults in Kundasang (Azhari, 2012). The results of the 3-year study indicated active surface movement in Kundasang in the range of several cm per year. What caused the surface movement, however is not conclusive, as Kundasang area is also riddled with surface movements associated with landslides. During the past ten years or so JUPEM has been monitoring the overall movement of Sabah using its Global Navigation Satellite System (GNSS) stations in Sabah. Preliminary analysis of the GNSS data by Mustafar *et al*. (2014) indicate lateral and vertical movements between 2-11 mm/year, whereas extension and compression movements between stations are very small at less than 1 mm/year.

Based on the presence of earthquakes, mud volcanoes, hot springs coupled with remote-sensing analysis and field surveys carried out for the last few years several prominent active and potentially active faults in Sabah have been identified (Figure 9). The active faults can be grouped into compressional structures (thrust and strike-slip faults) and extensional structures (normal faults). The thrust faults are mostly orientated ENW-WSW whereas the strike slip faults are mostly oriented NW-SW. The normal faults are mostly oriented NE-SW. The active faults mostly coincide with the location of ancient fault lines. Apart from observing active faults on alluvium and young sediments, active faults manifest on the ground as negative lineaments on radar image, some associated with triangular facets, mud volcanoes and hot springs. Continuous damage to particular stretches of roads also indicate the presence of active faults.

Thrust and strike-slip faults

Evidence for thrust and strike-slip faults are mostly found in the Lahad Datu-Tawau area in southeast Sabah. The Lahad Datu-Tawau area and its vicinity exhibit numerous linear features (20-40 km in length), mostly associated with earthquakes (Figure 10). Three main directions predominate, namely NW-SE, NE-SW and roughly WNW-ESE. The presence of active NW-SE and NE-SW trending faults in the field has been observed in several places associated with fault scarps, road damages, mud volcanoes and hot springs.

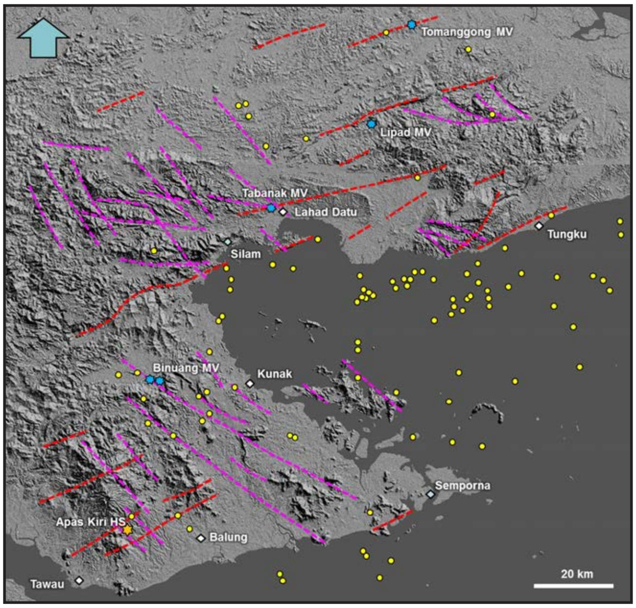

Figure 10: SRTM image of SE Sabah showing prominent negative lineaments, coinciding with the locations of earthquake epicentres (yellow circle), mud volcanoes (MV) and hot springs (HS), which could be active faults. Three trends dominates, NW-SE, NE-SW and WNW-ESE representing thrust faults (red line) and strike-slip faults (purple line). The earthquakes are provided by MetMalaysia.

At the western end of the Lahad Datu Airport, near Kg. Tabanak N65E trending faults showing both horizontal and vertical movements were observed (Figure 11). The NE-SW fault showing right lateral horizontal movement has caused a split in a coconut tree trunk. A semi-active Tabanak mud volcano is located near the faults. The presence of both horizontal and vertical movements may be related to trans-extension regime related to NE-SW right lateral shearing. The Tabanak mud volcano was seen to be also associated with strike-slip faults (Tongkul, 1989). Near Lahad Datu town area, the NW-SE trending fault can be inferred from the location of two persistent damaged roads (Figure 12). Another NW-SE fault showing horizontal movement can be observed passing through a newly-cut road.

Several mud volcanoes can be observed in the Dent Peninsula region. The most spectacular one occur near Tabin, known as the Lipad Mud Volcano (Figure 13). The Lipad mud volcano shows signs of uplift indicating a NW-SE compression direction. Cones located on the mud volcano are oriented NE-SW possibly related to active faults. Mud volcanoes are also common around the Tomanggong area, where they are located along a NE-SW trend (Figure 14). Several mud volcanoes such as the Binuang Mud Volcanoes are aligned NW-SE in the Kunak area (Figure 15). Several

Figure 11: Active faults associated with a Tabanak mud volcano near Lahad Datu Airport showing E-W compression. (A) The active fault movement trending N65E has caused a split in the trunk of two coconut trees. (B & C) The dextral strike-slip fault splitting the coconut trees. (D) Vertical movement associated with a strike-slip faults further south. See Figure 10 for location.

Figure 12: (A) Active strike-slip fault associated with two persistent road depressions aligned NW-SE at Lahad Datu town. (B & C) The damaged road sits on Miocene Tabanak Formation. (D) NW-SE trending slickensides associated with sinistral strike-slip fault on the Tabanak Formation. See Figure 10 for location.

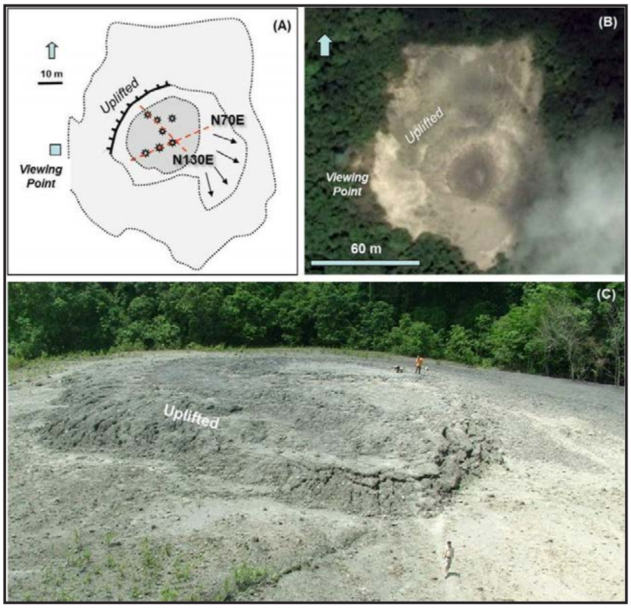

Figure 13: The Lipad Mud Volcano showing active NW-SE compression in Lahad Datu area. (A) Morphological sketch of the area showing the distribution of the mud volcano cones aligned N70E and N130E. (B) The Lipad Mud Volcano seen on satellite image. (C) The mud volcano seen from the viewing point showing the uplifted part on the NW.

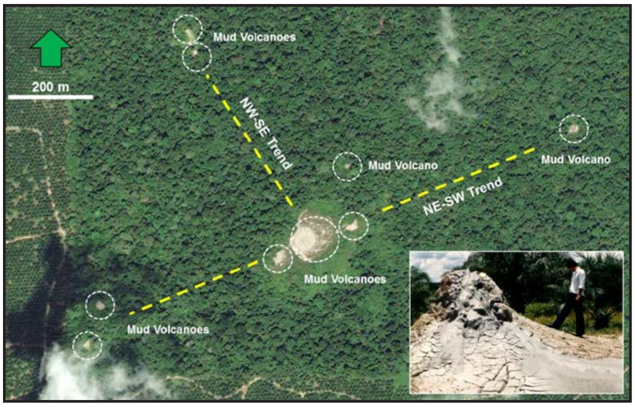

Figure 14: Satellite image showing the distribution of mud volcanoes in the Tomanggong area, Lahad Datu aligned in a NE-SW and NW-SE directions associated with active faults. One of the mud volcanoes (inset). See Figure 10 for location.

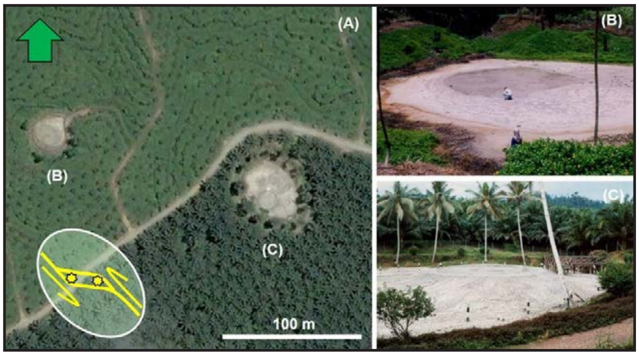

Figure 15: Satellite image showing mud volcanoes inside Binuang Plantation in Kunak possibly associated with NW-SE sinistral shearing (inset). See Figure 10 for location.

hot springs can be found around the Tawau Hills Park area. The most spectacular one is located at the upper part of Sg. Apas Kiri (Figure 16). The hot springs appear to be aligned in a NW-SE direction, possibly related to active faults in this region.

Normal faults

Evidence for active normal faults is mostly found in western Sabah along the NW-SE trending inland valleys of the Crocker-Trusmadi Range. The Tenom, Keningau, Tambunan and Ranau basins filled with Quaternary sediments show distinctive linear features on one of its side associated with triangular facets (Figure 17). Lengths of individual basins and associated faults range from about 20 to about 60 km. In the northern part of Tenom valley, normal faults trending NE-SW and dips towards the northwest cuts through young Quaternary sediments (Figure 18). Tjia (2007) included these fault segments as part of the Crocker Fault Zone. Similar extensional structures occur in the Ranau Valley, whereby normal faults trending NE-SW dipping both to the northwest and southeast are seen cutting through the Holocene Pinousuk Gravel (Figure 19).

NE-SW trending normal faults characterized by linear valleys and fault scarps can be found in Kundasang area on the southern foot of Mount Kinabalu (Figure 20). The NE-SW scarps coincide with the Lobou-Lobou Fault, which is thought to have generated the Magnitude 6, 2015 Ranau earthquake. Apart from the normal fault scarps, evidence for strike slip faults can also be found here, whereby a series of negative lineaments trending NW-SE cuts through the south-flowing Mesilou River. The left-lateral displacements along the Mesilou River are possibly related to the movements of the Mesilou faults. The presence of the Lobou-Lobou and Mesilou fault trends has been observed in a Holocene Pinousuk Gravel quarry section near Kg. Mesilou. In the quarry section, the NE-SW trending normal faults dip towards the NW cutting through the nearly vertical NW-SE strike-slip faults. The numerous road subsidence and displacement along the Kundasang-Mesilou road trending NW-SE may be related to the movements of these active faults.

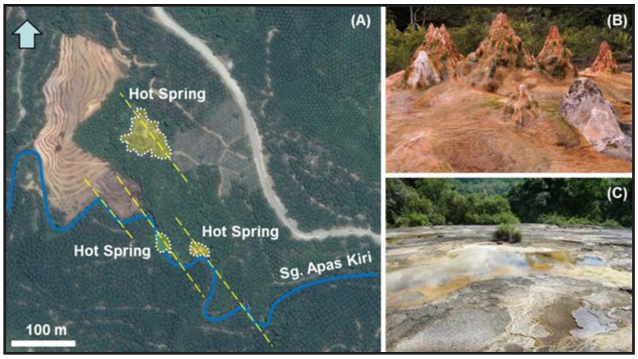

Figure 16: (A) Satellite image showing location of three main clusters of Sg. Apas Kiri hot springs aligned in a NW-SE direction associated with active faults (yellow line). (B) Conical spouts from the hot springs. (C) Steaming ground with travertine deposits produced by the hot springs. See Figure 10 for location.

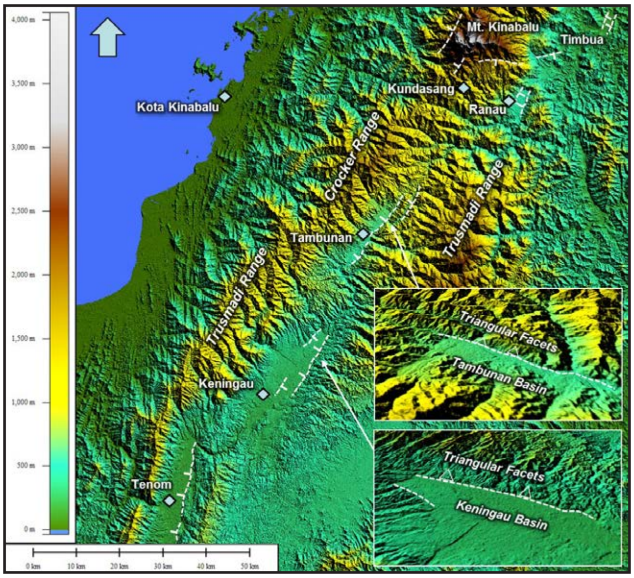

Figure 17: SRTM image showing the segmented linear extensional basins trending approximately NE-SW along the Crocker Range, stretching from Tenom to Ranau. Triangular facets (insets) indicate dominant down-throw towards the northwest.

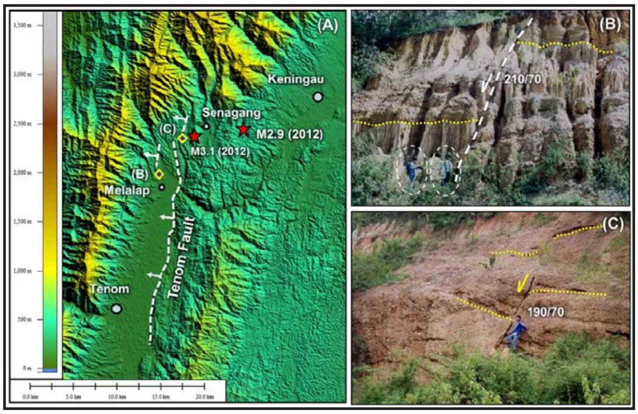

Figure 18: Extensional tectonics around Tenom Basin. (A) NNE-SSW trending Tenom Fault seen on SRTM image. Red star shows location of 2012 earthquake epicenters. (B) Normal fault dipping towards the NW on Quaternary gravels near Senagang Village. (C) Normal fault dipping towards the west on Quaternary gravel near Melalap Village.

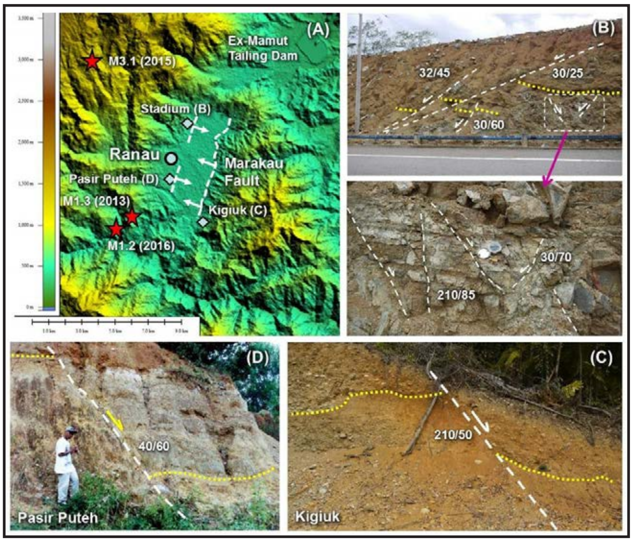

Figure 19: (A) NNE-SSW trending Marakau Fault seen on SRTM image around Ranau Basin. Red star shows location of recent earthquakes. (B) Normal faults trending NE-SW dipping southeast on ultrabasic rocks near the Ranau Stadium. (C) Normal fault showing 1 m displacement on Quaternary Pinousuk Gravel near Kigiuk Village dipping towards the NW. (D) Normal fault showing 3.5 m displacement on Quaternary Pinousuk Gravel dipping towards the SE near Taman Pasir Puteh.

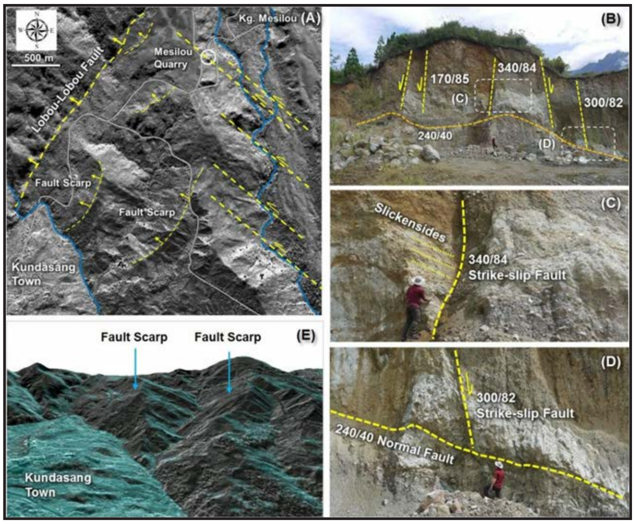

Figure 20: (A) IFSAR image showing NE-SW Lobou-Lobou normal fault zone and NW-SE strike-slip Mesilou fault zone in the Kundasang area. (B) Normal and strike-slip faults seen in Mesilou Quarry. (C) Nearly vertical strike-slip fault trending NW-SE. (D) The strike-slip fault is cut through by younger normal fault trending NE-SW and dipping towards the NW. (E) NE-SW trending fault scarps associated with the Lobou-Lobou Fault.

DISCUSSION: ACTIVE TECTONIC REGIME

Sabah is currently under a WNW-ESE compressive stress regime due to the effect of westward moving Philippine-Pacific plate (about 10 cm/year) against the southeast moving Eurasian plate (about 5 cm/year). The WNW-ESE compression is being accommodated by NE-SW trending active thrust faults and NW-SE trending active strike-slip faults all over Sabah (Figure 21). What is unexpected is the presence of the extensional stress regime within a compressive stress regime. This is of course, not uncommon, as both stress regimes co-exist along subduction-accretionary fold-thrust belts such as those in Java and Sumatra (Tingay *et al*., 2010). The current hypothesis to explain the presence of extensional regime has been attributed to gravitational forces generated by high topography by Sapin *et al*. (2013) and Hall (2013). They even suggested that the ongoing compressive tectonics along the NW Borneo Trough maybe linked to gravitational forces. However, it is unlikely that only one process is involved. The regional distribution of the normal faults and the characteristics of the normal faults showing dip direction both to the NW and SE suggests that it might be due to a combination of compressional tectonics due to collision and gravity sliding.

The regional structures of onshore Sabah, dominated by obducted Mesozoic ophiolitic rocks, folded and thrust-faulted Paleogene sedimentary rocks and gently folded Miocene sedimentary rocks indicate that Sabah has undergone NW-SE shortening since the late Tertiary. Offshore Sabah, similar compressional structures occur along the NW Borneo Trough (Hess *et al*., 2009). King *et al*. (2010) attributed the present-day shortening in the Baram Delta toe fold-belt with far-field compression, apart from gravitational tectonics.

The shortening, associated with thrust faults, may have resulted in the thickening of the upper crust as the Dangerous Grounds continental crust is being overthrust by the Sabah ophiolitic oceanic crust (see Figure 21). According to Cottam *et al*. (2011) and Hall *et al*. (2009) Sabah has been massively uplifted since early Miocene, with the Kinabalu pluton emplaced during the early Late Miocene and being exhumed at a rate of 7 mm per year during Late Miocene–Early Pliocene (~ 8–3 Ma ago) as the region continues to rise at a long term rate of about 0.5 mm each year. According to Hall (2013) the uplift is thought to be a result of either break-off of the subducted slab or delamination of the lithosphere.

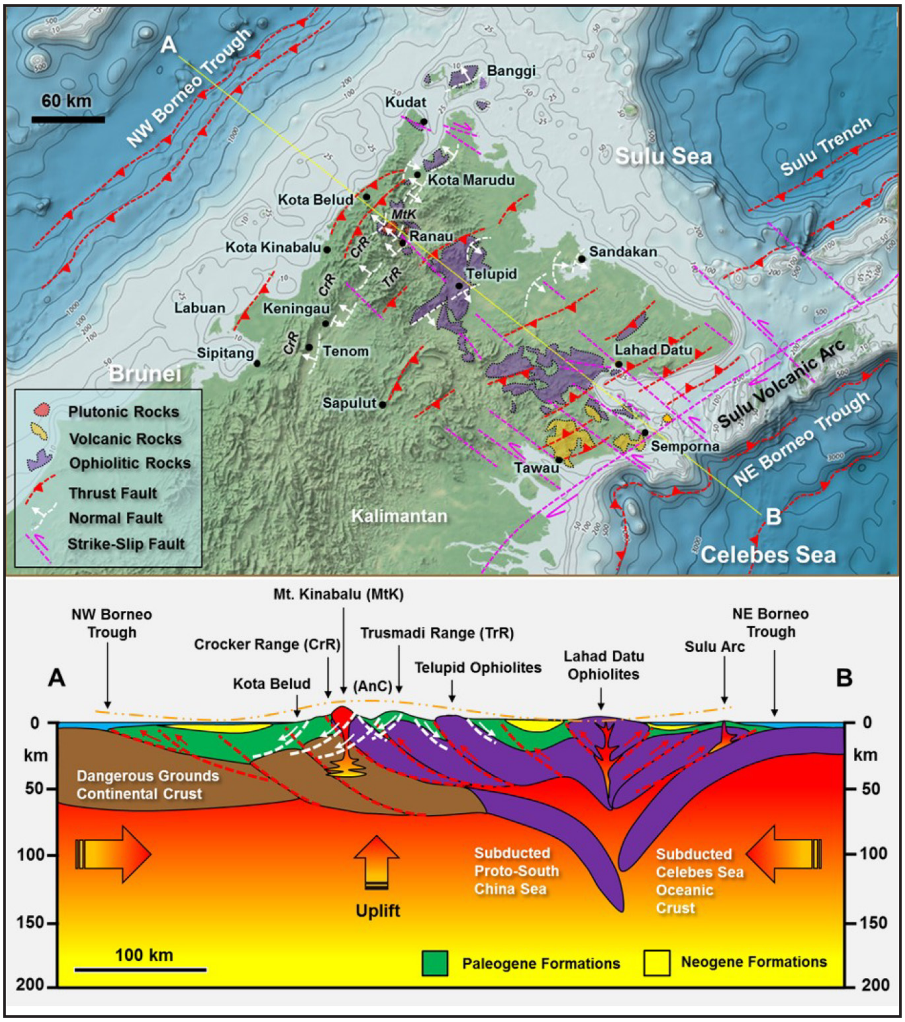

Figure 21: Schematic diagram to illustrate the regional active faults associated with shortening of Sabah due to ongoing WNW-ESE tectonic compression. The overthrusting of the Dangerous Grounds continental crust with the Sabah Ophiolites resulted in thickening, warping and uplift of the crust along the Crocker Range (CrR) and Trusmadi Range (TrR). The crest of the anticlinorium (AnC) became the site of extensional tectonics forming a series of graben-like basin from Tenom to Kota Marudu. The other half-graben normal faults may be associated with deep-seated gravitational sliding towards the South China Sea and Celebes Sea.

At the collision zone an uplifted belt trending NE-SW, more than 200 km in length, developed where the present Crocker and Trusmadi ranges are located. The collision may also be associated with the warping or gentle regional folding of the upper crust. The crest and flanks of the anticlinorium became the site of NE-SW trending extensional tectonics. Some of the normal faults associated with the elongate NE-SW Quaternary basins that stretch from Tenom to Kota Marudu showing full graben structure possibly indicate the location of the crest of the anticlinorium. The other normal faults, characterized by half-graben along the Crocker Range and Telupid areas maybe associated with deep-seated gravity sliding towards the South China Sea and Celebes Sea, respectively, due to the difference in elevations of the upper crust.

CONCLUDING REMARKS

. Active tectonics, both compressional and extensional, is very much alive in Sabah based on the occurrence of earthquakes and presence of active faults accommodating plate motions in the region. However, the crustal movement is quite small and its surface expressions are not easily discernible. Identification of active faults in Sabah is still a big challenge. Further study using GPS to monitor the movement of active faults may provide some indication on the slip rates of these faults. INSAR study over a period of time could also mapped out minute ground movements associated with the active faults. Seismic tomography may provide insight into the origin of the deep-seated extensional structures in Sabah.

ACKNOWLEDGEMENTS

I would like to thank Universiti Malaysia Sabah for providing logistic support for this research. This study was made possible with support from the Malaysian Ministry of Higher Education (Project FRG0093-ST-1/2006) and the Malaysian Ministry of Science and Innovation (Project 04-01-10-SF0201). The local earthquake data was provided by the Department of Meteorology Malaysia. I thank all my colleagues in UMS, UM, UKM and JMG for their contribution in the ongoing discussion on active faults study in Malaysia. I would also like to thank Franz L. Kessler and Mustaffa K. Shuib for their constructive comments.

REFERENCES

Azhari Mohamed, 2012. Monitoring Active Faults in Ranau, Sabah Using GPS.19th United Nations Regional Cartographic Conference for Asia and the Pacific, Bangkok, 29 October – 1

November 2012.

Cottam, M.A., Hall R., Sperber C., Kohn B.P., Forster M.A. & Batt G.E., 2011. Neogene rock uplift and erosion in northern Borneo: evidence from the Kinabalu granite, Mount Kinabalu. Journal of the Geological Society, 70, 805–816.

Hall, R., Cottam, M.A., Suggate, S., Tongkul, F., Sperber, C. & Batt, G., 2009. The Geology of Mount Kinabalu. Sabah Parks Publication, 13.

Hall, R., 2013. Contraction and extension in northern Borneo driven by subduction rollback. Journal of Asian Earth Sciences, 76, 399-411.

Hesse, S., Back, S. & Franke, D., 2009. The deep-water fold-and-thrust belt offshore NW Borneo: Gravity-driven versus basement-driven shortening. Geological Society of America Bulletin, 121(5-6), 939-953.

Ismail, A.R., Tongkul, F., Mustaffa, K.S., Tajul, A.J., Alexander, Y.S.W., Mohd Rosaidi, C.A., Noraini, S., Rozaini, I., Mohd Nazan, A., Ferdaus, A., Mohamad, M., Bailon, G., Henry, L.A., Ledyhernando, T., Zaidi, D., Roziah, C.M., Zahid, A., Rabieahtul, A.B., Khamarrul, A.R. & B., Harry, 2015. Remote sensing and field survey analysis of active faults in tectonically active areas in Malaysia. Sciencefund Project 04-01-10-SF0201 Technical Report for MOSTI. 124 p.

JMG, 1985. Geological Map of Sabah, 3rd Edition, Ministry of Natural Resources and Environment.

JMG, 2006. Study on the seismic and tsunami hazards and risks in Malaysia. Report on the geological and seismotectonic information of Malaysia. Ministry of Natural Resources and Environment. 47 p.

JMG, 2008. Seismotectonic Map of Malaysia, 3rd Edition, Ministry of Natural Resources and Environment.

King, R.C., G. Backe´, C.K. Morley, R.R. Hillis & M.R.P. Tingay, 2010. Balancing deformation in NW Borneo: Quantifying plate-scale vs. gravitational tectonics in a delta and deepwater fold-thrust belt system. Marine and Petroleum Geology, 27, 238–246.

Leyu, C.H., Chang, C.F, Arnold, E.P., Kho, S.L., Lim, Y.T., Subramaniam, M., Ong, T.C., Tan, C.K., Yap, K.S., Shu, Y.K. & H.L. Goh, 1985. Southeast Asia Association of Seismology and Earthquake Engineering Series on Seismology, Volume III – Malaysia.

Lim, P.S. & Godwin, P., 1992. The Ranau earthquake swarm, May-July 1991, Sabah. Proc. 23rd Geol. Conf. Geol. Survey Malaysia, 4, 168-193.

Lim, P.S., 1976. Earth tremors in Eastern Sabah. Malaysia Geological Survey Annual Report 1976, 220-223.

Lim, P.S., 1985. History of earthquake activities in Sabah, 1897-1983. Geological Survey Malaysia Annual Report, 1983, 350-357.

Lim, P.S., 1986. Seismic activities in Sabah and their relationship to regional tectonics. Geological Survey of Malaysia Annual Report 1985, 465-480.

Michel, G.W., Becker, M.,Angermann, D., Reigber, C. & Reinhart, E., 2001. Crustal motion and block behaviour in SEAsia from GPS measurements, Earth Planet. Sci. Lett.,187, 239 – 244.

Mustafar, M.A., W.J.F. Simons, K.D. Omar & B.A.C. Ambrosius, 2014. Monitoring of Local Deformations in North Borneo. Proceedings of FIG Congress 2014, Engaging the Challenges, Enhancing the Relevance, Kuala Lumpur, Malaysia, 16 – 21 June 2014.

Sapin, F., Hermawan, I., Pubellier, M., Vigny, C. & Ringenbach, J.-C., 2013. The recent convergence on the NW Borneo Wedge—a crustal-scale gravity gliding evidenced from GPS. Geophysical Journal International, 193(2), 549–556.

Simons, W.J.F., Socquet, A., C. Vigny, B.A.C. Ambrosius, S. Haji Abu, Chaiwat Promthong, C. Subarya, D.A. Sarsito, S. Matheussen, P. Morgan & W. Spakman, 2007. A decade of GPS in Southeast Asia: Resolving Sundaland motion and boundaries. J. Geophysics Res., 112, B06420.

Tingay, M., C. Morley, R. King, R. Hillis, D. Coblenz & R. Hall, 2010. Present-day stress field of South East Asia. Tectonophysics, 482, 92-104.

Tjia, H.D., 1978. The Lahad Datu (Sabah) earthquake of 1976: surface deformation in the epicentral region. Sains Malaysiana, 7(1), 33-64.

Tjia, H.D., 2007. Kundasang (Sabah) at the intersection of regional fault zones of Quaternary age. Geological Society of Malaysia Bulletin, 53, 59-66.

Tongkul, F., 1989. Recent strike-slip fault movement associated with a mud volcano in the Lahad Datu area, Sabah. Sains Malaysiana, 18(1), 23-31.

Tongkul, F., 1990. Structural style and tectonics of western and northern Sabah. Bull. Geol. Soc. Malaysia, 27, 227-239.

Tongkul, F., 1991. Tectonic evolution of Sabah, Malaysia. Journ. Southeast Asian Earth Science, 6(3/4), 395-405.

Tongkul, F., 1997. Polyphase deformation in the Telupid area, Sabah, Malaysia. Journ. Southeast Asian Earth Sciences, 15(2-3), 175-183.

Tongkul, F., 1992. The Ranau earthquake: possible causes. Sabah Society Journal, 9(4), 315-322.

Tongkul, F., 2016. The 2015 Ranau Earthqauke: Cause and Impact. Sabah Society Journal, 32, 1-28.

Tongkul, F. & Omang, S.A.K., 2010. Geological studies of active faults in Ranau and Lahad Datu Areas, Sabah. Final report of FRGS Project FRG0093-ST-1/2006 submitted to MOHE.

Walpersdorf, A., C. Vigny, C. Subarya & P. Manurung, 1998. Monitoring of the Palu-Koro Fault (Sulawesi) by GPS. Geophysical Research Letters, 25(13), 2313-2316.

Wilford, G.E., 1967. Earth tremors in Sabah. Sabah Society Journal, 3, 136-138.

Manuscript received 11 October 2016
Revised manuscript received 9 February 2017
Manuscript accepted 29 June 2017