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Intraplate crustal deformation in Sabah: Preliminary results of Global Positioning System/Global Navigation Satellite System measurements in the Ranau area

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Abstract: The Ranau area is one of the most earthquake-prone areas in Sabah due to the ongoing intraplate deformation in the region. Numerous active faults have been mapped here, but to date these faults are yet to be fully documented in terms of their exact locations and movements. Since 2018, the Department of Mineral and Geoscience (JMG) has installed and monitored 31 GPS/GNSS (Global Positioning System/Global Navigation Satellite System) monuments in the Ranau area to determine crustal movements in this region. Preliminary results show minor horizontal and vertical movements (ranging from 0.1 cm to 4.3 cm) indicating that the Ranau area is undergoing intraplate crustal deformation due to both NW-SE compressional and extensional tectonics. A clear demarcation of upward and downward vertical movements recorded in areas to the NW and SE of Kundasang could be related to uplift and subsidence associated with a large open anticline and syncline. A consistent northwestward horizontal movement from Kundasang to Kota Belud indicates the presence of a single crustal block moving away from the NE-SW trending Lobou-Lobou Fault Zone. Southwestward horizontal movement in the Nalapak-Nabutan area indicates the presence of a NW-SE trending fault possibly associated with the Matupang Fault Zone. These preliminary results show that the GPS/GNSS campaign has proven to be quite successful in locating the major earthquake-generating faults in the Ranau area. However, the locations and nature of the movements of other active faults are still uncertain. It is hoped that the activity of these faults will become clearer after a few more years of monitoring.

Keywords: GPS/GNSS velocities, intraplate crustal deformation, active faults, Ranau, Sabah

INTRODUCTION

The Ranau area in Sabah is known to be a tectonically active area with high seismic activity, as demonstrated by the June 2015 Ranau earthquake with magnitude 6.0 on the Richter scale. Sabah is located near the boundaries of three major tectonic plates, the Eurasia Plate, Philippine Sea Plate and Indo-Australian Plate, moving at a rate of 5 cm per year, 10 cm per year and 7 cm per year, respectively. The collision of the rifted southern border of the Eurasian Plate (Sundaland and South China Sea Basin) with the westward and northward moving Philippine Sea Plate and Indian-Australian Plate, respectively, have caused intraplate crustal deformation in Sabah since the late Tertiary (Figures 1 & 2). The ongoing crustal deformation has resulted in active faulting in Sabah (Tongkul, 2017). An earthquake focal mechanism solution shows that both compressional stress regime (producing active thrust faults and strike-slip faults) and extensional stress regime (producing active normal faults) occur in Sabah (Figure 3). The compressional stress regime is mostly recorded in Southeast Sabah (Lahad Datu and Kunak areas), whereas the extensional regime is mostly recorded in West Sabah (Ranau and Kundasang areas) and North Sabah (Kudat area).

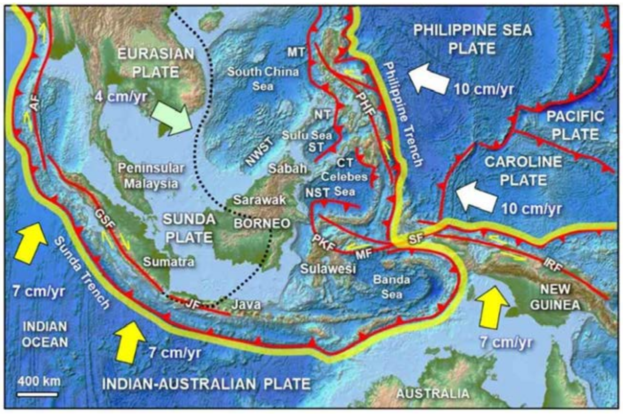

Figure 1: Tectonic setting of Sabah showing major plate boundaries (thick yellow line) and plate movements (arrows). Sabah lies hundreds of kilometer away from active plate boundaries of the Philippine Trench (Tongkul, 2017).

While numerous active and potentially active faults have been identified in Malaysia (Ismail *et al.*, 2015), their exact locations and movements have yet to be determined with certainty due to the lack of a geodetic monitoring system in place. Most of the active faults have been inferred based on geomorphological features, geophysical studies and their

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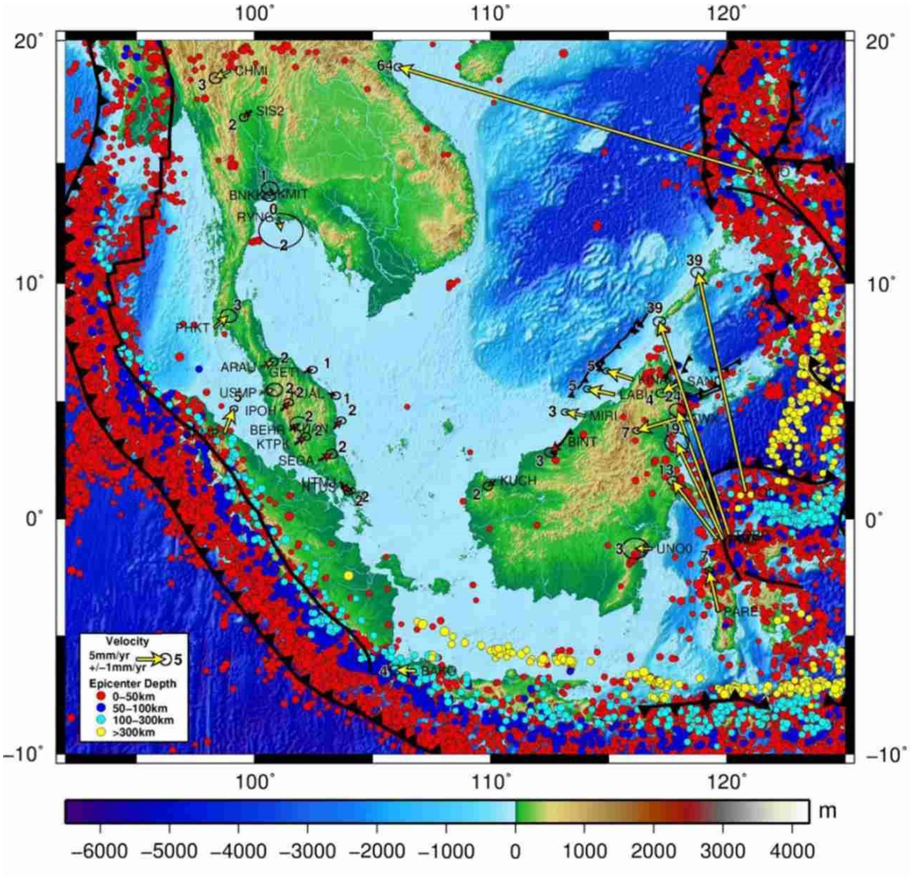


Figure 2: Earthquake epicentres in Southeast Asia (Source: USGS). Also shown are the regional GPS station velocities around Borneo with respect to Sundaland (Mustafar *et al*., 2017). The GPS stations show large WNW and NNW movement of microblocks from Sulawesi and Philippines, respectively. Sabah shows small movement towards the WNW relative to an undeformed Sundaland.

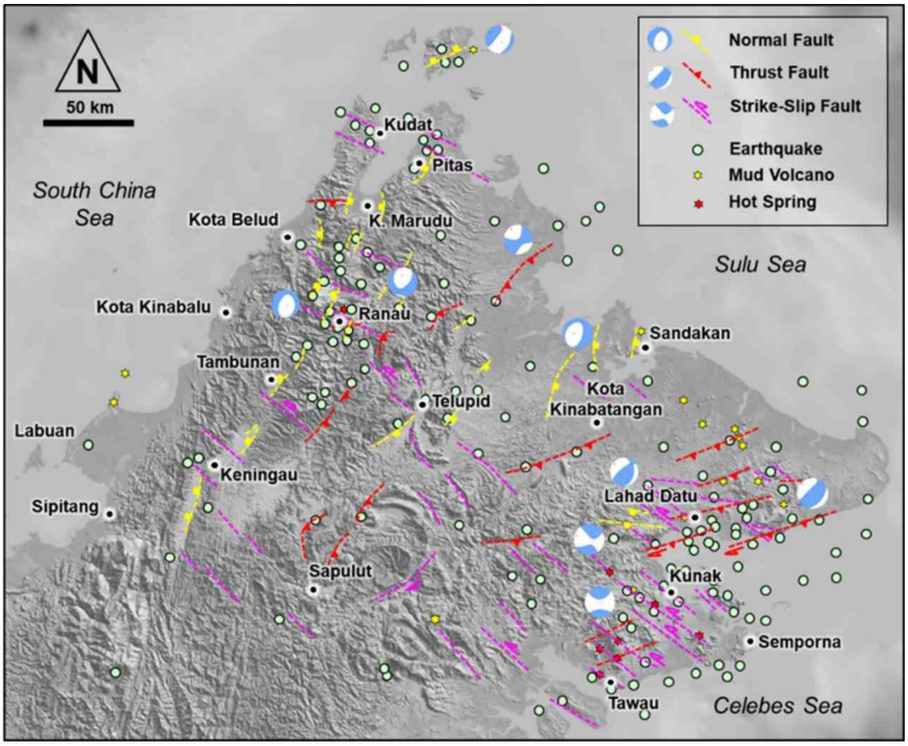


Figure 3: Location of potential active faults in Sabah. The potential active faults trending NE-SW in West Sabah are mostly normal faults whereas the faults trending NW-SE and NE-SW in East Sabah are strike-slip faults and thrust faults (based on Tongkul, 2017). The corresponding focal mechanisms (beach balls) indicate the presence of both extensional and compressional regimes in Sabah.

associations with earthquakes, mud volcanoes and hot springs. Earlier studies using limited Global Navigation Satellite System (GNSS) data have determined minor intraplate crustal deformation in Sabah (Simons *et al*., 2007; Mohamed, 2012; Sapin *et al*., 2013; Mustafar *et al*., 2014 & 2017). Mustafar *et al*. (2017) have shown the presence of extensional and compressional stresses as well as a small clockwise rotation in Sabah (Figure 4). Due to the long distances (tens of km) between the GNSS stations, crustal deformation data are not so useful in determining local movement of active faults.

In an attempt to understand active fault movements in Sabah, the Department of Mineral and Geoscience Malaysia (JMG), in 2018 embarked on measuring intraplate crustal deformation using denser GPS/GNSS stations in the Ranau and Lahad Datu areas. This paper reports some of the early results of this GPS/GNSS campaign in the Ranau area.

GEOLOGICAL BACKGROUND

The tectonic setting of Sabah has been discussed since the early 70's by several authors, such as Tokuyama & Yoshida, 1974; Hamilton, 1979, Holloway, 1982; Wood, 1985, Rangin *et al*., 1990; Tan & Lamy, 1990; Tongkul, 1990, 1991; Hinz *et al*., 1991; Hall, 1996; Hutchison *et al*., 2000; Hall & Wilson, 2000 and Hall, 2013. Subduction of the Proto-South China Sea underneath Sabah ceased in the Early Miocene (Holloway, 1982; Rangin *et al*., 1990; Tan & Lamy, 1990; Hinz *et al*., 1991; Hall, 1996; Hutchison *et al*., 2000; Hall & Wilson, 2000; Hall, 2013). The convergent movement of the proto-South China Sea rifted block towards the southeast has influenced the geological structures in the west and north of Sabah (Tongkul, 1990). That movement ended by the Early Miocene to Middle Miocene (Taylor & Hayes, 1983; Briais *et al*., 1993; Barckhausen & Roeser, 2004). As a result, there was a major uplift that created the NE-SW trending Crocker Range on the west coast of Sabah (Hall, 2013). This elevated mountain range is undergoing gravitational instability and spreading towards NW Sabah Trough (Hall, 2013; Sapin *et al*., 2013).

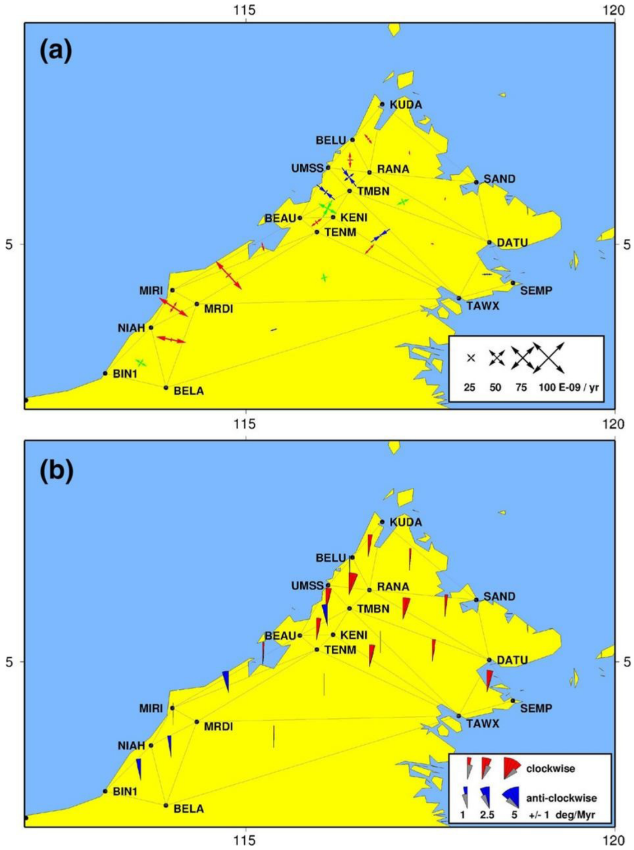


Figure 4: GPS strain and rotation rate tensors of North Borneo (2009–2011 solution) based on limited GPS stations (labelled black dots). (a) Red arrows show extensional deformation, blue arrows represent compressional deformation (shortening), and green arrows indicate shear deformation. (b) Red wedges represent clockwise rotation rates and blue wedges denote anti-clockwise rotation rates (Mustafar *et al*., 2017). Rotation is measured in reference to stable Sundaland.

The exact age of the uplift event in West Sabah is unknown (Hall, 2013), but the erosional episode related to the Deep Regional Unconformity (DRU) is believed to have occurred during the Middle Miocene (Bol & van Hoorn, 1980; Levell, 1987; Hutchison, 2004, 2005). Within the Crocker Range in West Sabah, an igneous plutonic body that forms Mount Kinabalu was intruded within the boundaries of the Ranau and Kota Belud districts. Mount Kinabalu is a granitic intrusion and has a summit height of approximately 4095 m above mean sea level and is assumed to be still rising at a long term rate of about 0.5 mm/year (Hall *et al*., 2009). The Ranau region is characterized by high seismicity and most earthquakes occur at depths of less than 50 km. The seismic activity in the Ranau region is caused by active faults. Research by JMG in 2006 and 2008 has identified five faults in the Ranau region, such as the Lobou-Lobou Fault, Mensaban Fault, Mamut Fault, Parancangan Fault and Nalapak Fault (Yan *et al*., 2008). These findings need to be further investigated by mapping and strain deformation analysis.

PREVIOUS GEODETIC RESEARCH IN SABAH

Sabah appears to be slowly moving and/or deforming independently while undergoing clockwise rotation with respect to the rigid Sundaland block (Rangin *et al*., 1990; Simons *et al*., 2007; Sapin *et al*., 2013; Mustafar *et al*., 2017). Researchers such as King *et al*. (2010), Sapin *et al*. (2013) and Hall (2013) interpreted crustal movements in the western part of Sabah as being driven by gravity sliding. Other researchers such as Simons *et al*. (2007), Franke *et al*. (2008), and Hesse *et al*. (2009) interpreted the deformation of West Sabah as mainly due to crustal shortening.

Compression and extension observed in offshore Sabah have accommodated the remaining convergence between Sundaland and Philippine Sea plates in this region (Franke *et al*., 2008 and Hesse *et al*., 2009). Sapin *et al*. (2013) proposed extensional collapse of the Crocker Range as the main mechanism to balance the extensional deformation deficit in the offshore. Some authors have suggested that the extensional collapse of the Crocker Range had caused compression in offshore West Sabah, creating the deepwater fold thrust-belt that hosts the hydrocarbon accumulations and future exploration targets (Ingram *et al*., 2004; Morley *et al*., 2011).

There has been ongoing debate on the tectonic setting of Western Sabah due to the lack of a Global Navigation Satellite Systems (GNSS) network in place there. The strong earthquake in Ranau on 5 June 2015, with a magnitude of 6.0ML is proof of active deformation in the western part of Sabah. Hence, it is necessary to undertake geodetic monitoring in more detail particularly in the Ranau Central region. GNSS has become a valuable tool for geological studies and correlation of past and current tectonic activities. The Global Positioning System (GPS) was a pioneering tool for the study of crustal deformation during the past three decades. Now a more advanced technology in the GNSS system is being used extensively to study earth deformation. The Department of Survey and Mapping Malaysia (JUPEM) carried out a GNSS campaign with continuous monitoring in Sabah known as the Malaysia Real Time Kinematic GNSS Network (MyRTKnet). However, this network only monitors regional plate movements and does not detect local crustal movements, such as those occurring in the the central Ranau region. GNSS data from JUPEM networks in Sabah were examined by Mustafar *et al.* (2017) who quantified the recent deformation of Sabah using the latest continuous GNSS data set.

The first geodetic campaign using GNSS was carried out in Kundasang, Sabah, in 2010 by JUPEM and JMG. Passive monuments for GNSS monitoring were installed in the Kundasang area within the Lobou-Lobou Fault zone and Mensaban Fault zone. The results of monitoring showed displacement between 3-5 cm per year (Mohamed, 2012). In quantifying the recent deformation of Sabah, Mustafar *et al*. (2017) computed GNSS station positions that are used to defined the Sundaland block motion in the International GNSS Service (IGS) realization based on IGS08 (Rebischung *et al*., 2012) and the International Terrestrial Reference Frame 2008 (ITRF, 2008; Altamimi *et al*., 2011). He concluded that that gravity sliding did not occur as Sapin *et al*. (2013) had found and suggested further investigation to be carried out to evaluate the geological data in western Sabah region.

ACTIVE SEISMOTECTONIC SETTING OF THE RANAU AREA

Based on remote-sensing analysis and field observations, Ismail *et al*. (2015) mapped at least seven major main active fault zones, which can be grouped into three main trends, NE-SW, NW-SE and WSW-ENE (Figure 5). These fault zones are associated with both compressional and extensional tectonics. The NE-SW faults are normal faults down-throwing to the NW and SE. They are informally named as the Kinabalu Fault Zone, Lobou-Lobou Fault Zone, Ranau Fault Zone, Timbua Fault Zone and Matupang Fault Zone. The NW-SE faults, named informally as the Mensaban Fault Zone, are strike-slip faults showing left lateral horizontal movements. The WSW-ENE faults are mostly likely thrust faults with right lateral horizontal movements; they are informally named the Kibbas Fault Zone. These fault zones which comprise several faults coincide with the location of significant earthquake epicenters (Figure 5). Based on preliminary findings, this research have mapped a total of 18 major faults, namely Lobou-Lobou Fault, Mensaban Fault, Kedamaian Fault, Nalapak Fault, Lipasu Fault, Ranau Fault, Kibbas Fault, Nabutan Fault, Matupang Fault, Merungin Fault, Serinsim Fault, Kijuhutan Fault, Kapuakan Fault, Kinapasan Fault, Lakang Fault, Poring Fault, Kundasang Fault and Tarawas Fault (Figure 6). Three of these faults, namely Lobou-Lobou Fault, Mensaban Fault and Nalapak Fault, were classified as active faults by Tjia (2007) and Yan *et al.* (2008). The movement of most of these faults is yet to be confirmed as field mapping and verification is still in progress.

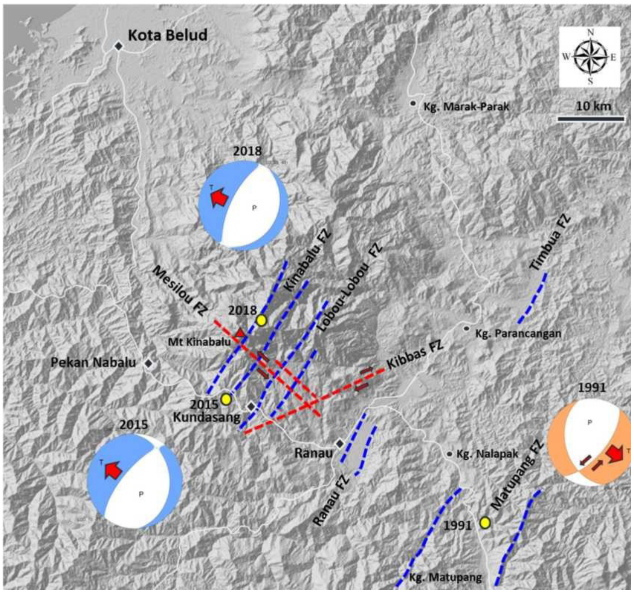


Figure 5: Summary of the main active fault zones (FZ) in the Ranau area (based on Ismail *et al.*, 2015), comprising normal faults (blue) and strike-slip faults (red). The normal faults are the Kinabalu Fault Zone, Lobou-Lobou Fault Zone, Ranau Fault Zone, Timbua Fault Zone and Matupang Fault Zone whereas the strike-slip faults are the Mensaban Fault Zone and Kibas Fault Zone. Significant earthquake epicenters (1991, 2015 and 2018) shown as yellow circles are from USGS database. The fault mechanism solutions of the earthquakes (blue and orange beach balls) indicate NE-SW oriented normal faults. The 1991 earthquake show significant left lateral movement.

GPS/GNSS DATA ACQUISITION AND PROCESSING

A total of 31 GPS/GNSS monuments - 3 active and 28 passive monuments - were installed by JMG in Ranau and the surrounding districts in 2018; three active monuments

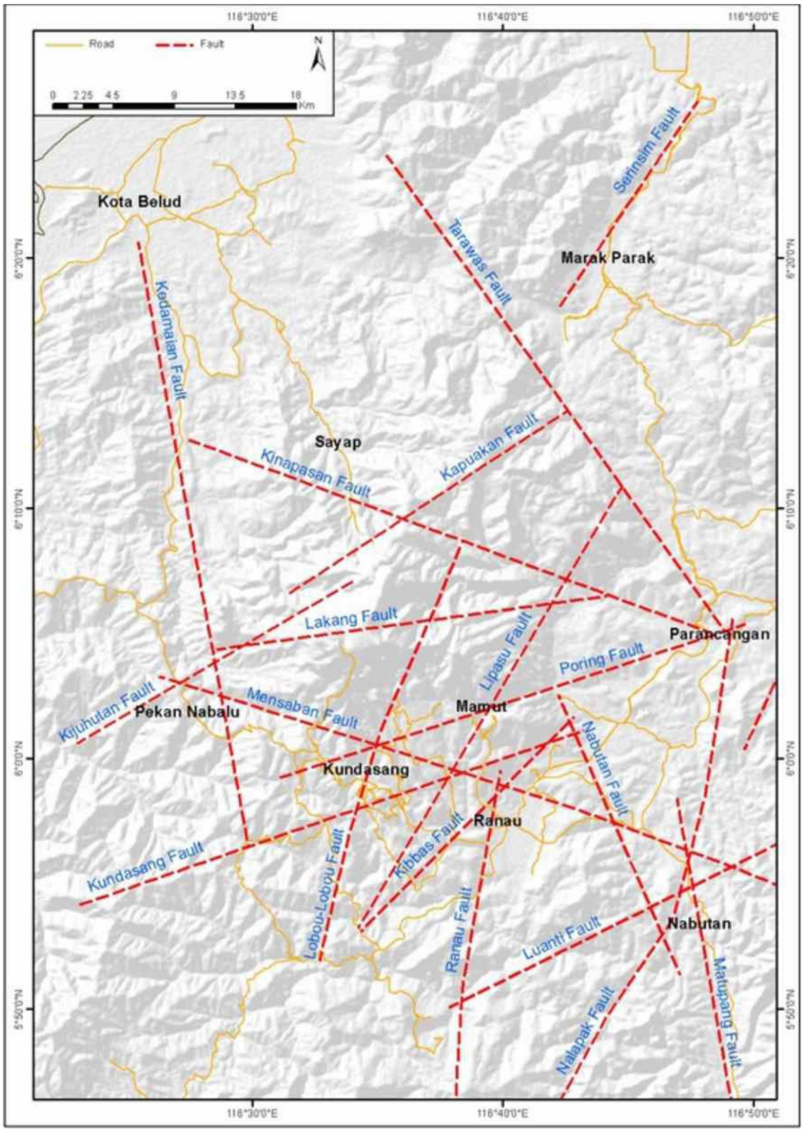


Figure 6: Occurence of major faults in Ranau area, trending NW-SE, NNW-SSE, E-W, NE-SW, NNE-SSW and ENE-WSW.

and 28 passive monuments as shown in Figure 7. The active monuments are located at MetMalaysia office; Marakau (MKU); Sabah Tea, Nalapak (NPK) and SMK Agama Mohamad Ali (SMA); whereas the passive monuments are located at Kg. Bundu Tuhan (BTN); Rose Cabin (RCN); Kg. Kinasaraban (KSN); Kg. Desa Aman (DMN); Kg. Dumpiring Atas (DTS); Kem Bina Negara (KBN); Pine Ridge (PRE); Kg. Mesilou (MSU); Kg. Kauluan (KLN); SK Longut (LGT); Kg. Lipasu Lama (LSU); Kompleks Sukan Ranau (KSR); Base Camp Ranau (BCP); Mamut (MUT); SMK Tambulion Kota Belud (TLN); Kg. Tamu Darat (TDT); Kg. Sayap Kota Belud (SYP); Kg. Pirasan, Kota Belud (PRN); Hospital Kota Marudu (HKM); Serinsim, Kota Marudu (SRM); Kg. Perancangan (PCN); Kg. Waluhu, Matupang (WLU); Toboh Baru (TBU); Kg. Kundasang Lama (KLA); Kg. Himbaan (HBN) and Gunung Kinabalu (GKU).

The active monuments at MetMalaysia office, Marakau (MKU), was set as a reference point or a base station whereas the other monuments (NPK & SMA) were used as rovers for monitoring. The selection of GPS/GNSS sites were guided by the locations of major faults, besides their accessibility, geological conditions, stability, security and logistics (Figure 7). After selecting a suitable site, augering and mackintosh jobs were carried out to study the soil lithology, ground stability, type of bedrock and depth of bedrock (Photo 1a). The passive monuments are monitored regularly using Trimble R10 GNSS surveying tools (Photo 1b), whereas the active monuments are monitored continuously from JMG office in Kota Kinabalu.

GPS/GNSS monitoring of 28 passive monuments were carried out over a period of 2 years in September 2018, November 2018, March 2019, October 2019, June 2020 and October 2020, whereas the three active monuments were monitored continuously for one year (September 2019 – October 2020). The post-processing correction of GNSS passive data were carried out using

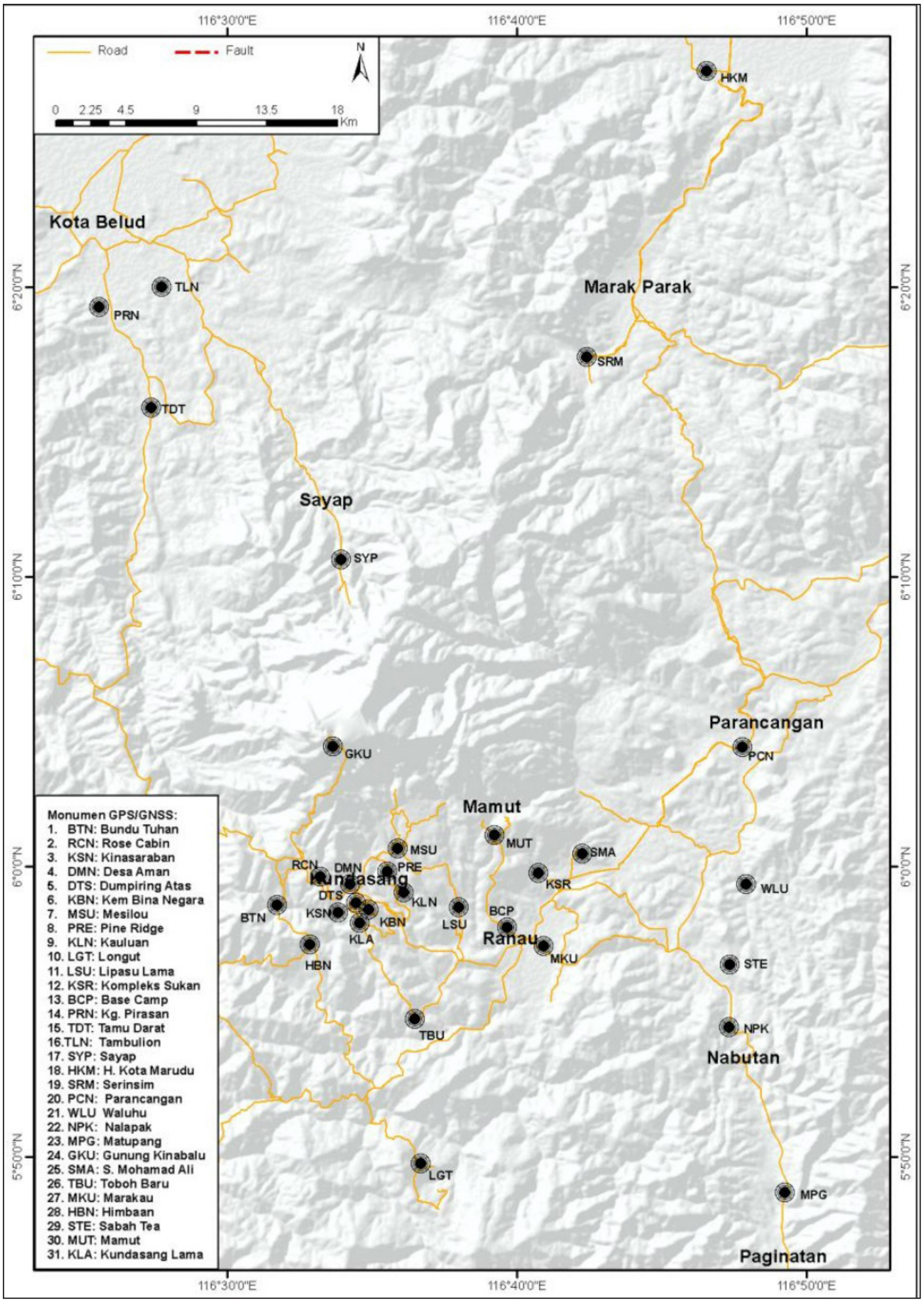


Figure 7: Locations of 31 monuments for monitoring selected major faults. More densely located monuments were installed around Kundasang area to monitor established active faults here.

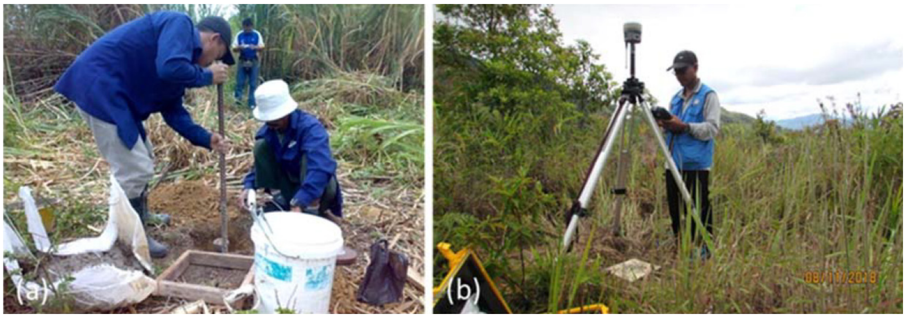


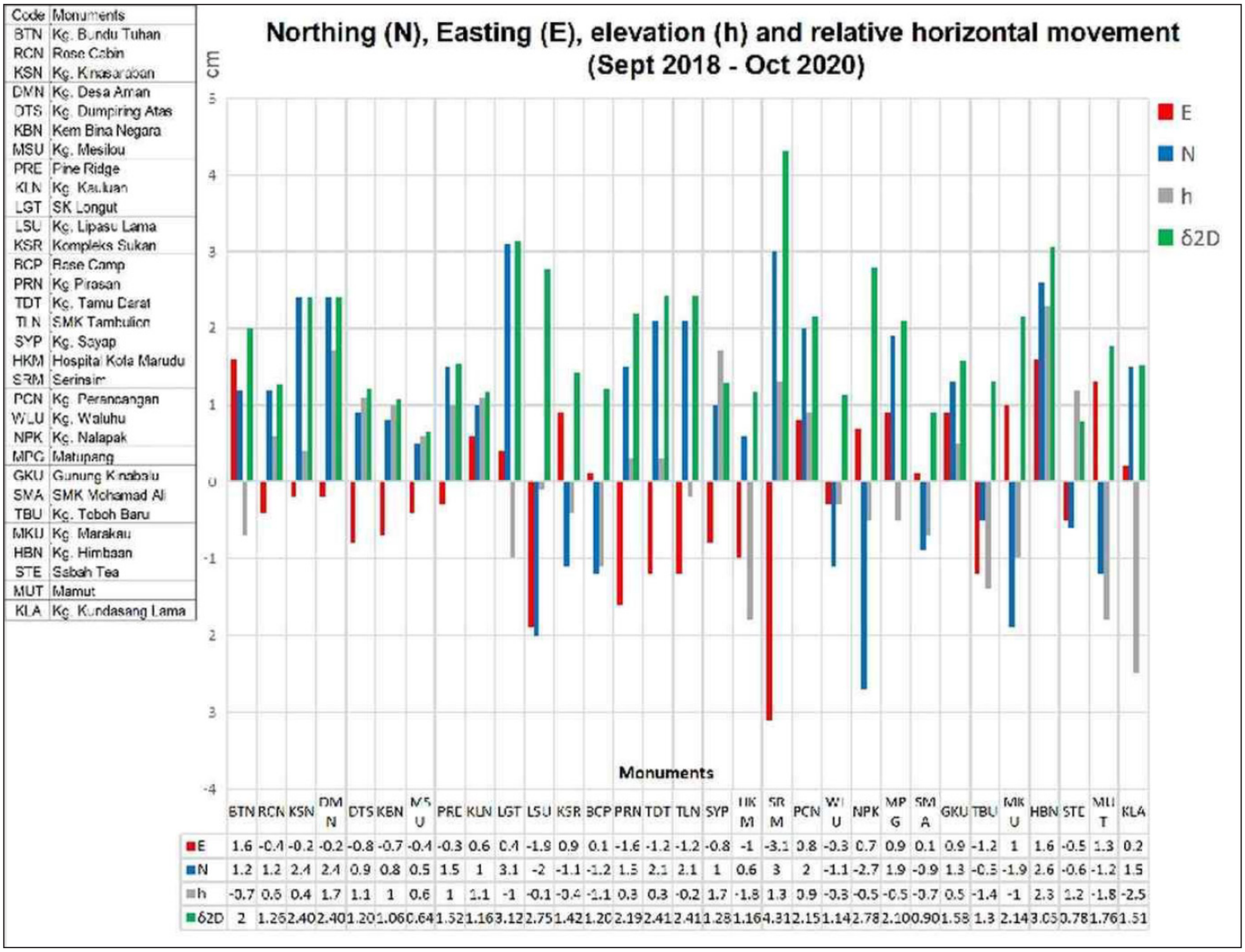
Photo 1: (a) Preparation of a monument site, (b) Data observation on passive monument using Trimble R10 GNSS surveying tool.

T4D Control software provided by Trimble. The GNSS monitoring uses the static GNSS surveying method. The processing and analysis of GPS observations were performed using Trimble Total Control software and also T4D Control software analysis tool. The study uses the International Terrestrial Reference Frame 2014 (ITRF2014) as its datum. The post-processing of data uses the Borneo RSO Timbalai 1948 coordinate system to get a 2D displacement for easting (x) and northing (y) coordinates with respect to Sundaland Plate movement. A positive value for x indicates movement towards East whereas negative value for x indicates movement towards West. A positive value for y indicates movement towards north whereas negative value for y indicates movement towards south. The real-time monitoring using Trimble NetR9 has a high degree of reliability and accuracy. The horizontal accuracy is 3 mm + 0.1 ppm RMS and 8 mm + 0.5 ppm RMS for networked RTK, whereas the vertical accuracy is 3.5 mm + 0.4 ppm RMS and 15 mm + 0.5 ppm RMS for networked RTK.

PRELIMINARY RESULTS

The results from the 28 passive monuments measured for a period of 2 years and 3 active monuments for a period of 1 year show minor relative horizontal and vertical movements (ranging from 0.1 cm to 4.3 cm) (Figure 8). The largest horizontal movement of 4.3 cm was recorded from the passive monument at Serinsim (SRM), whereas the largest vertical movements of 2.3 cm (upwards) and 2.5 cm (downwards) was recorded at Kg. Himbaan (HBN) and Kg. Kundasang lama (KLA), respectively. The real-time measurements from the three active stations show that the horizontal velocity ranges from 6 mm to 12 mm per year, whereas the vertical velocity ranges from -8 mm to +7 mm per year.

The horizontal movements (0.8 – 4.3 cm) show six directions, NW, NE, SW, SE, NNW and S (Figure 9). Eleven monuments located northwest of Kundasang moved towards the NW, namely RCN, DTS, KBN, MSU, BCP, TDT, TLN, SYP, HKM, SRM and TBU. Eight monuments moved towards the NE; these include six monuments located in Kundasang area, namely BTN, LGT, KLA, KLN, HBN,



Code	Monuments
BTN	Kg. Bundu Tuhan
RCN	Rose Cabin
KSN	Kg. Kinasaraban
DMN	Kg. Desa Aman
DTS	Kg. Dumpiring Atas
KBN	Kem Bina Negara
MSU	Kg. Mesilou
PRE	Pine Ridge
KLN	Kg. Kauluan
LGT	SK Longut
LSU	Kg. Lipasu Lama
KSR	Kompleks Sukan
BCP	Base Camp
PRN	Kg. Pirasan
TDT	Kg. Tamu Darat
TLN	SMK Tambulion
SYP	Kg. Sayap
HKM	Hospital Kota Marudu
SRM	Serinsim
PCN	Kg. Perancangan
WLU	Kg. Waluhu
NPK	Kg. Nalapak
MPG	Matupang
GKU	Gunung Kinabalu
SMA	SMK Mohamad Ali
TBU	Kg. Toboh Baru
MKU	Kg. Marakau
HBN	Kg. Himbaan
STE	Sabah Tea
MUT	Mamut
KLA	Kg. Kundasang Lama

	BTN	RCN	KSN	DMN	DTS	KBN	MSU	PRE	KLN	LGT	LSU	KSR	BCP	PRN	TDT	TLN
🟥 E	1.6	-0.4	-0.2	-0.2	-0.8	-0.7	-0.4	-0.3	0.6	0.4	-1.9	0.9	0.1	-1.6	-1.2	-1.2
🟦 N	1.2	1.2	2.4	2.4	0.9	0.8	0.5	1.5	1	3.1	-2	-1.1	-1.2	1.5	2.1	2.1
⬜ h	-0.7	0.6	0.4	1.7	1.1	1	0.6	1	1.1	-1	-0.1	-0.4	-1.1	0.3	0.3	-0.2
🟩 δ2D	2	1.26	2.40	2.40	1.20	1.06	0.64	1.52	1.16	3.12	2.75	1.42	1.20	2.19	2.41	2.41

	SYP	HKM	SRM	PCN	WLU	NPK	MPG	SMA	GKU	TBU	MKU	HBN	STE	MUT	KLA
🟥 E	-0.8	-1	-3.1	0.8	-0.3	0.7	0.9	0.1	0.9	-1.2	1	1.6	-0.5	1.3	0.2
🟦 N	1	0.6	3	2	-1.1	-2.7	1.9	-0.9	1.3	-0.3	-1.9	2.6	-0.6	-1.2	1.5
⬜ h	1.7	-1.8	1.3	0.9	-0.3	-0.5	-0.5	-0.7	0.5	-1.4	-1	2.3	1.2	-1.8	-2.5
🟩 δ2D	1.28	1.16	4.31	2.15	1.14	2.78	2.10	0.90	1.58	1.3	2.14	3.05	0.78	1.76	1.51

Figure 8: Relative horizontal and vertical movements (cm) of monuments in the study area.

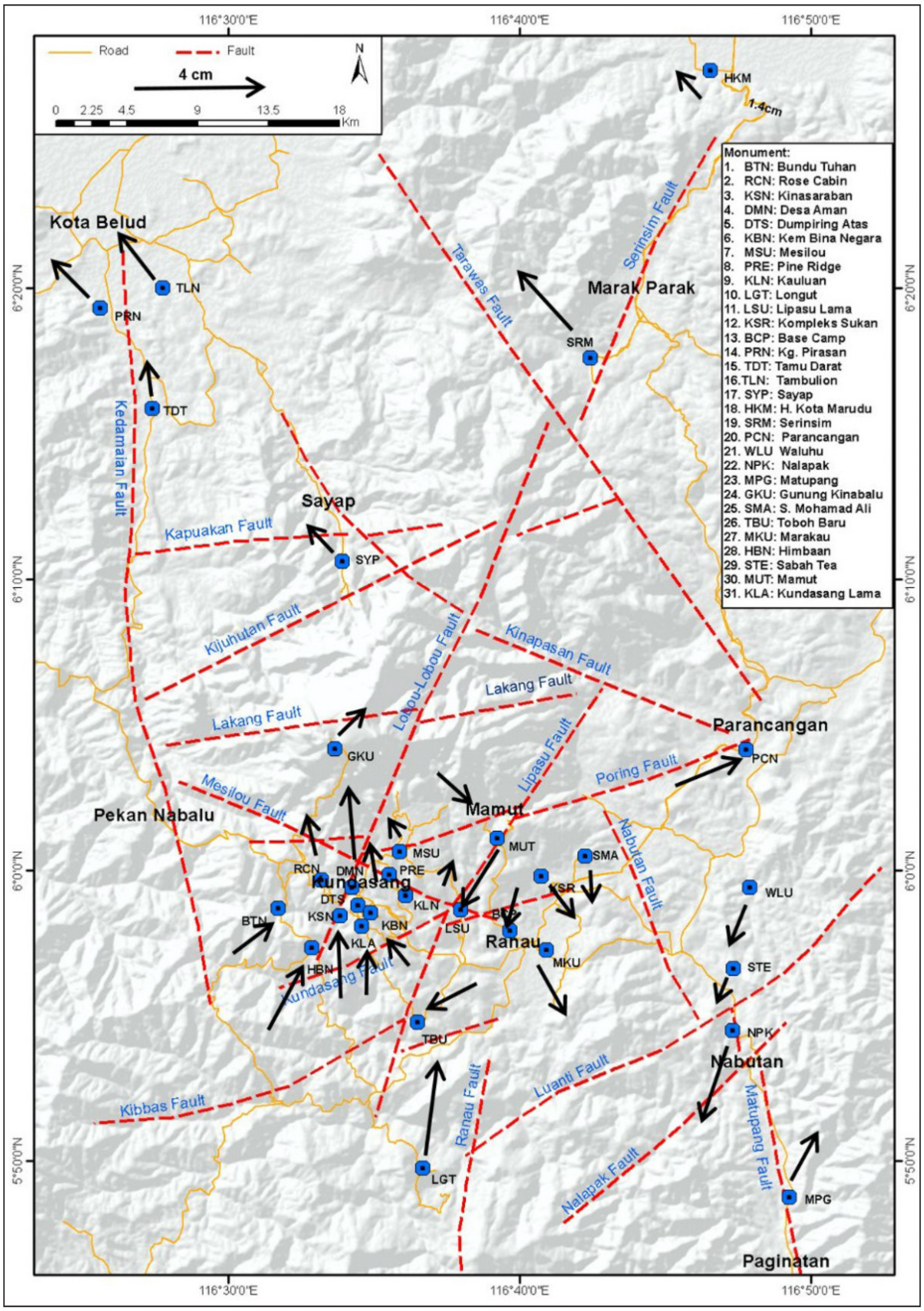


Figure 9: Relative horizontal movement direction of monuments in Ranau from September 2018 until October 2020.

PCN and GKU and two located in Ranau area, namely LGT and MPG. Five monuments located in Ranau area moved towards the SW, namely WLU, STE, LSU, BCP and TBU. There are three monuments showing movement towards the SE namely KSR, MUT and MKU. Three monuments located in Kundasang area moved towards the NNW, namely KSN, DMN and PRE. Only SMA monument moved towards the south.

For vertical movements, show 16 monuments were moving upwards and 15 monuments moving downwards (Figure 9). The monuments that moved upwards (0.4 – 2.3 cm) are RCN, KSN, DMN, DTS, KBN, MSU, PRE, KLN, PRN, TDT, SYP, SRM, PCN, GKU, HBN and STE, whereas the monuments that moved downwards (0.1 – 2.5 cm) are BTN, LGT, LSU, KSR, BPC, TLN, HKM, WLU, NPK, MPG, SMA, TBU, MKU, MUT and KLA.

DISCUSSION

The different magnitude of horizontal and vertical movements recorded from the 31 monuments during a short period of two years indicate that the Ranau area is undergoing complex intraplate crustal deformation. The movements could be associated with the presence of several active faults located close to each other.

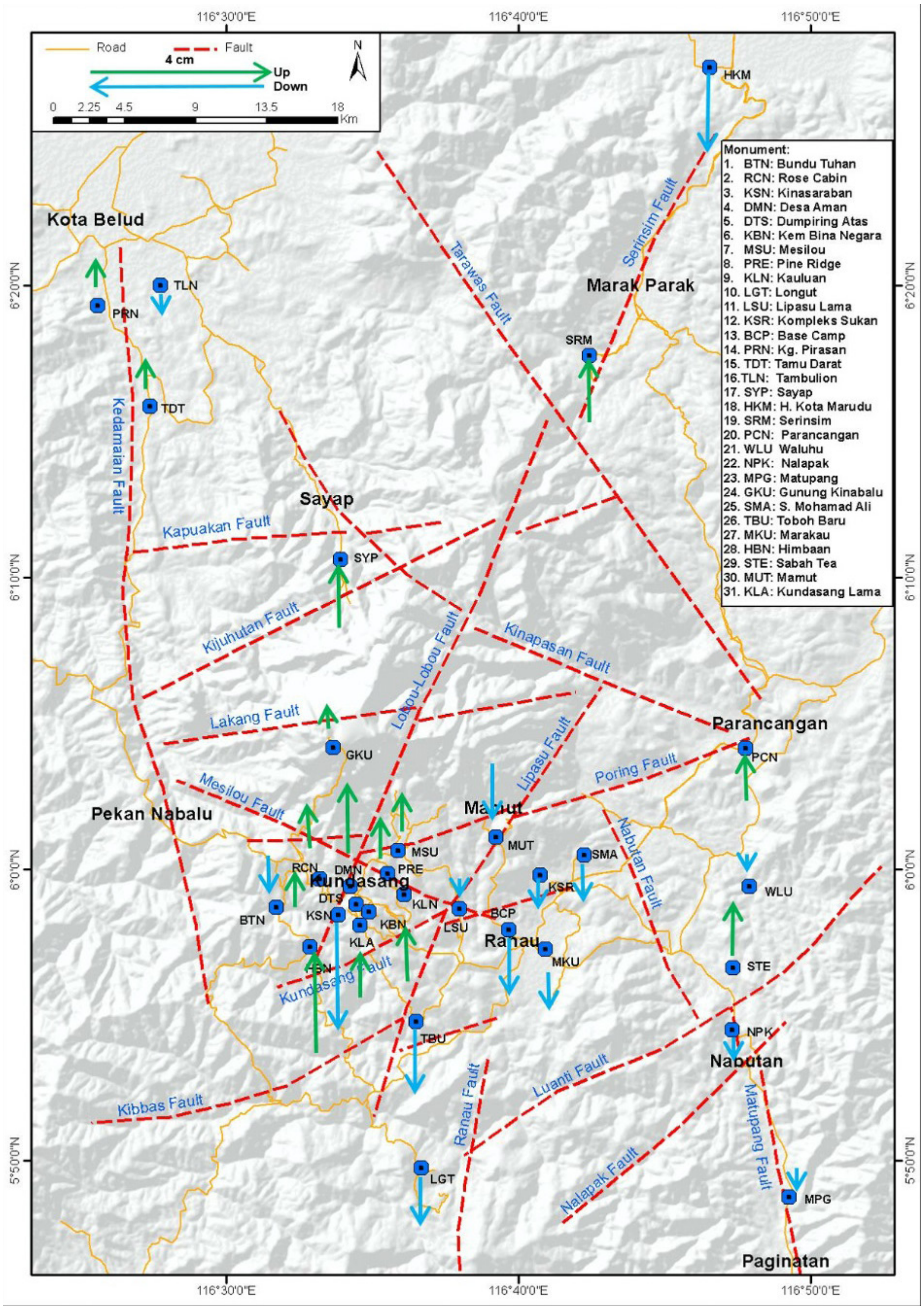


Figure 10: Vertical movement recorded from monuments from September 2018 until October 2020 in Ranau.

The opposing horizontal movement directions towards the NW and SE appears to be associated with stretching (extension) of the crust around Kundasang area (Figure 11). The crustal extension is generally consistent with NW movement which suggests that Kundasang and Kota Belud areas moved as a single crustal block. The NW movement could be related to the dip-slip of a major active NE-SW normal fault located between Kundasang and Ranau area. This area is currently occupied by the Lobou-Lobou Fault Zone. This interpretation is in agreement with the focal mechanism solutions of the 2015 and 2018 Ranau Earthquakes which indicate a similar normal fault orientation at this location. The different magnitude of movement towards NW could be associated with different amount of shortening deformation within the same block. The area southeast of Kundasang shows quite diverse horizontal movements towards SE and SW. The SE movement could be associated with a major normal fault dipping in the opposite direction to the Lobou-Lobou Fault Zone located near Ranau town area. The SW-directed movement could be associated with a sinistral strike-slip movement of a major NE-SW normal fault dipping SE, possibly located between Nabutan and Matupang area. This interpretation is in agreement with the focal mechanism solution of the

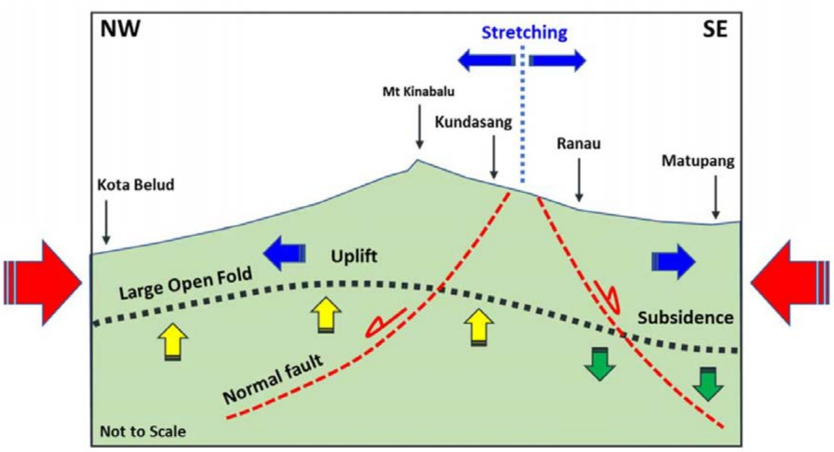


Figure 11: Schematic model to explain the horizontal and vertical movements in the Ranau area. The on-going NW-SE tectonic compression of Sabah resulted in a large open fold, causing very small magnitude of crustal uplift and subsidence. Normal faulting between Kundasang and Ranau caused the NW and SE horizontal movements.

1991 Ranau Earthquake which indicates similar sinistral horizontal movement on the NE-SW trending normal fault in this location.

The vertical movement shows a general pattern of upward movements located northwest of Kundasang area and downward movements located to the southeast. This pattern suggests that the two areas are located on different blocks. The cause of these upward and downward vertical movements is uncertain but could be related to tectonic uplift and subsidence, respectively. The subsidence may be associated with a normal fault, whereas the uplift associated with a thrust fault. However, since both the uplift and subsidence occur opposite to each other they are more likely be associated with a large open fold (see Figure 11), whereby the uplifted area forms the core of the anticline (anticlinorium) whereas the subsided area forms the limb of the anticline. This idea of a large open fold was put forward by Tongkul (2017) to explain the co-presence of compressional and extensional tectonics in Sabah.

At this early stage of the study, it is difficult to ascertain the exact location and movement of the selected major faults in the Ranau area. Apart from the Lobou-Lobou Fault Zone in Kundasang area identified earlier, the location and movement of the remaining major faults remain speculative.

CONCLUDING REMARKS

Preliminary monitoring results from 31 GPS/GNSS monuments support the interpretation of the seismotectonic setting in Ranau area where both NW-SE compressional and extensional tectonics occur. Upward and downward vertical movements between Ranau and Kundasang are interpreted as being associated with a large anticline and syncline, respectively, due to NW-SE compression. Consistent NW-directed horizontal movements from Kundasang to Kota Belud suggest the presence of a block moving away from Kundasang area associated with the NE-SW trending Lobou-Lobou Fault Zone, which was responsible for the 2015 and 2018 Ranau earthquakes. The horizontal movement towards SE around Nalapak-Nabutan area supports a NE-SW extension associated with the Matupang Fault Zone which was responsible for the 1991 Ranau earthquake. The GPS/GNSS campaign has proven to be quite successful in locating the major earthquake-generating faults in the Ranau area. The diverse horizontal movement directions around Ranau and Kundasang areas indicate that other active faults may be present and could be identified more clearly after a few more years of monitoring.

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AUTHOR CONTRIBUTIONS

BG conceptualized and wrote the manuscript. FT and BG carried out data and schematic model interpretations. IAR interpreted and drew the schematic tectonic model of Ranau region.

CONFLICT OF INTEREST

The authors declare there is no conflict of interest.

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