Monitoring of Local Deformations in North Borneo

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Key words: GNSS, deformation, North Borneo, Sundaland, SE Asia

SUMMARY

Large parts of SE Asia nowadays are located on the Sundaland block, a tectonic entity that appears to move independently from the Eurasian Plate. The island of Borneo is also considered being part of the Sundaland block along its eastern margin. In North Borneo, the highest mountain on Sundaland is situated: Mount Kinabalu with a height of ~4100 meters. As a result of past tectonic activity, the mountain is considered to be still rising with a long term rate of about 0.5 mm/yr. However, North Borneo seems to be also still deforming in a different way. The North Borneo region appears to be actively deforming therefore not making up a rigid part of Sundaland. Deformation of western parts of North Borneo appears to be driven by gravity gliding due to frontal fold-and-thrust belts. However, north-west of North Borneo is exhibiting different deformation patterns and the driving force behind it is part of an already long-lived scientific debate. Global Navigation Satellite System (GNSS) are an excellent tool to study crustal motion and deformations in detail. Since 2007, the Department of Surveying and Mapping Malaysia (DSMM) have established additional continuous GNSS stations along the coastal area of North Borneo. The primary limits in previous researches were due to the lack of sufficient continuous GNSS station coverage in the area. Also in order to study the present (relatively small) deformation patterns, a sufficiently long time data span is needed. Therefore, this region provides a great opportunity for an enhanced study of local deformation as already a three-year time span of GNSS data has now become available. Absolute and relative baseline positioning was used to analyze deformation in horizontal and vertical components. Surprisingly, analysis of the vertical GNSS displacements also appears to show an unexpected result.

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1. INTRODUCTION

North Borneo is part of the Sundaland block at its eastern margin. In North Borneo also the highest mountain on the Sundaland is located known as Mount Kinabalu. Mount Kinabalu was formed by melting rocks deep in the crust about eight million years ago (Hall et al., 2008; Sperber, 2009). It is almost entirely composed of granite with a 4095m summit height. Mount Kinabalu is assumed to be still continuous rising at long term rate of about 0.5 mm/yr due to a lag effect to the geophysical processes than once created it. This rising rate is in balance with the typical modern erosion rates associated with inactive tectonic areas (Sperber, 2009). Nonetheless, North Borneo does seem to be active also in the different way. North Borneo appears to move/deform differently from the rigid Sundaland block with a clockwise rotation (Simons et al., 2007; Sapin et al., 2013). In addition, a long-lived debate exists on whether active motion of North-West Borneo is driven by gravity gliding (King et al.,2010; Sapin et al., 2013). The lack of GNSS data is a main constraint towards a better analysis of the behaviour of NW Borneo. The present day geophysical processes inside North Borneo therefore make it a very interesting area to study. Moreover, the area is surrounded by petroleum reservoirs that are useful for future exploration. GNSS has been extensively used during the last two decades as a great space-geodetic tool for geodynamics studies. Starting mainly with campaign style repeated observations, then gradually turned into continuous observations. Nowadays, many continuous stations have become operational and this provides more opportunity towards a better understanding of the active tectonics in a plate boundary deformation zone. Purpose of this paper is to study the recent deformation of North Borneo using the latest continuous GNSS stations. The baselines analysis allows identifying both extension and compression in North-Borneo.

2. SEISMOTECTONIC OF NORTH BORNEO

The configuration of crustal plates in South East Asia is tectonically complicated. The North-West Trench (Palawan Trough) is a part of the most recent subduction zone between the South China Sea and North-West Borneo (Hall, 2002). The delta between Brunei and Sarawak is an active fold-and-thrust belt known as the Baram Delta. This active delta is supported by Ingram et al. (2004) and King et al. (1996) in their studies. Hutchinson et al. (2000) stated that the Baram Delta was sourced from uplift and deformation of the Crocker-Rajang accretionary complex which continued to the Quaternary period (0 – 2.59 million years ago). The Baram delta shows extensional tectonics on the seabed with north-west delta progradation and migration of the deformation front. The southern part of North-West Borneo shows an approximated balance between extension of the shelf area and compression of the deep-water area while the northern part is dominant by compression in the deep-water area (Hesse et al., 2009). A few of the major active faults that can be found between the Crocker

Range and the Trusmadi Range as shown in Figure 1. The Crocker Range is located in western Sabah where also Mount Kinabalu is situated. There are a few local fault zones that are intersecting each other and are assumed to be currently active (Alexander et al., 2006). The presence active deformation in North Borneo was supported by the historical seismicity since 1923 to Feb 2014. Most of the earthquakes happened close to coastal region of western Sabah., Several light earthquakes occurred in Ranau which is close to Mount Kinabalu, due to nearby active faults. The most recent earthquake happened on February 1st 2014 with a magnitude 4.6 at latitude 6.2 N, longitude 116.5 E and depth 17.3 km (USGS, 2014).

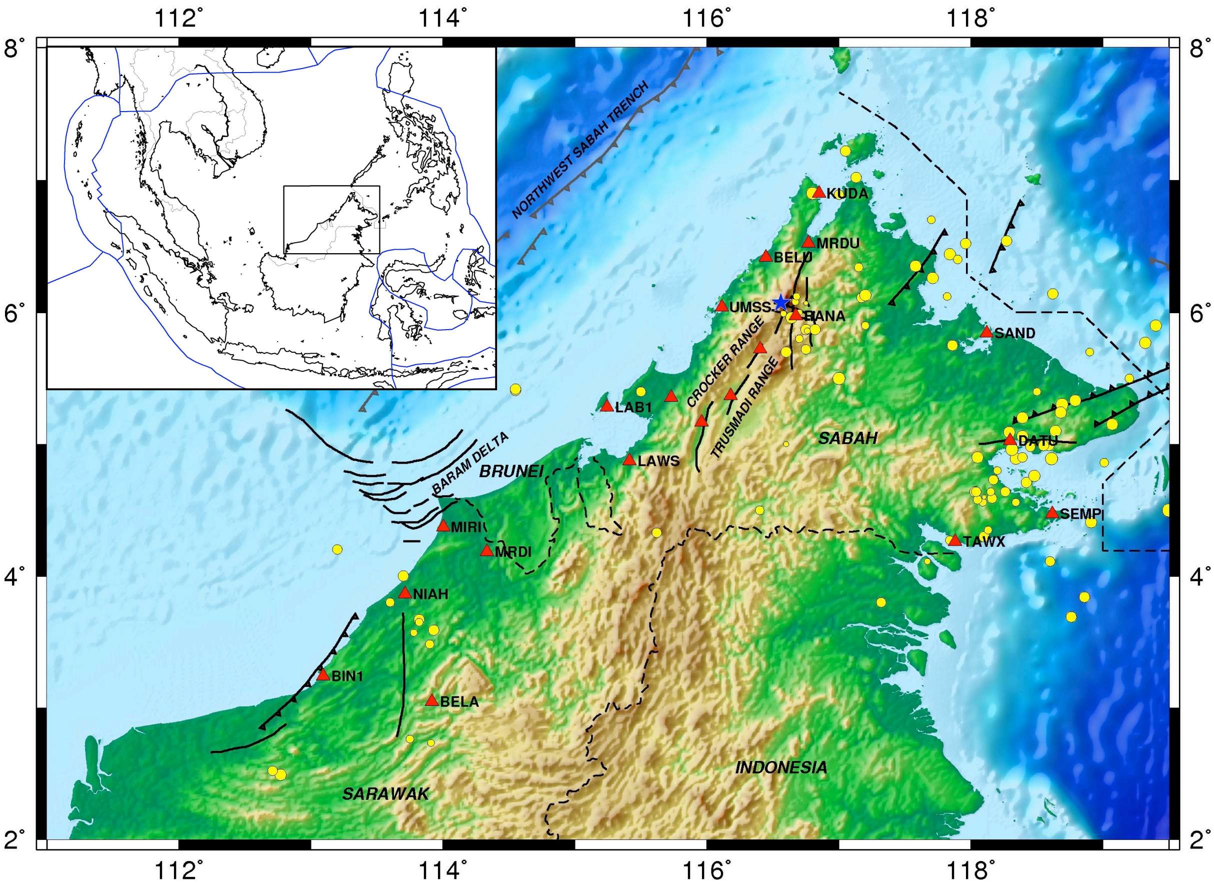

Figure 1: Main active fault (solid line), thrust fault (triangle line) and MyRTKnet stations (triangle) in North Borneo. The blue star represents Mount Kinabalu and circles are the earthquakes that occurred here from 1923 to February 2014 (Magnitude 1 to 6). Faults and trenches were extracted from Seismotectonic Map of Malaysia (Minerals and Geosciences Department Malaysia, 2009). The inset shows a South-East Asia map with main boundary of plates and blocks. The black box sketches the area of interest in this figure.

3. DATA AND PROCESSING

The Department of Surveying and Mapping Malaysia (DSMM) is a government agency which is responsible for establishing and maintaining GNSS stations in Malaysia known as the Malaysia Real-Time Kinematic GNSS Network (MyRTKnet). Since the end of 2007, DSMM has added more continuous GNSS stations in Borneo especially along the coastal area of North Borneo. The new GNSS stations are providing reliable data towards a detailed study of North Borneo. Unfortunately, few stations were shut down such as KINA and LABU whereby the latter station was replaced by LAB1. In 2008, many stations also have a data gap and noisy results. In order to have significant results, a three year data span for 20 stations was used between January 2009 and December 2011 (Figure 1).

The dual frequency GNSS data were processed using the scientific GIPSY-OASIS II software version 6.1.2. In this study, the Precise Point Positioning (PPP) was applied to derive precise coordinate results. Precise ephemeris of satellites along with Earth rotation parameters were taken from Jet Propulsion Laboratory (JPL). The GNSS data were processed in daily batches on 5 minutes interval of zero-differenced observables based on the linear ionospheric free combination. An elevation mask angle of 7 degrees was applied to the observation data. Absolute antenna phase center table were applied for taking into account the different GNSS antenna behaviour. A recent tropospheric mapping function known as Vienna Mapping Functions (VMF1) was used that is based on data from a numerical weather model. The database of VMF1 mapping coefficient grid was downloaded from the Global Geodetic Observing System website maintained by Vienna University of Technology (Boehm et al., 2006). Ocean loading effects using according to the FES2004 ocean tide model were retrieved from the Onsala Space Observatory (Bos & Schenneck, 2013). Daily station coordinates solutions were combined into daily solutions. Then Ambizap3 was used for fixing the phase ambiguities (Blewitt, 2008). This processing stage relies on double differencing, whereby the shorter baselines are processed first. Next the daily ambiguity-fixed solutions were mapped to the International Terrestrial Reference Frame (ITRF2008) using daily transformation parameters available from the x-files provided by JPL along with their ephemeris package (Altamimi et al., 2011). After mapping, the daily solutions were combined into weekly averages using seven-parameter Helmert transformations. At this stage, to increase the reliability of results, the daily solutions were screened and any outliers were down-weighted using a detection criteria based on the median absolute deviation (MAD) (Rousseeuw and Croux, 1993). Finally, the weekly-average solutions covering a three years period were used to construct and evaluate so-called position time series.

4. NORTH BORNEO MOTION

Poistion time series in ITRF2008 were used to estimate station velocities using linear regression. Analyzing any misfits (eg. position jumps) was performed in three-dimensional fitting of linear trends. This was accompanied by an iterative outlier detection step, which either marks all position components when a horizontal misfit is detected or just the vertical component if a height misfit is observed. Further details on the velocity estimation can be found in Simons et al. (2007).

4.1 Motion in ITRF2008

Figure 2 shows direction and magnitude of velocity for each station in ITRF2008. Magnitudes of stations range between 23 and 29 mm/yr. Stations on the west side are pointing to ~113 degrees ESE except LAWS and LAB1. Station LAWS has a strange direction that might be due to instability of the geodetic monument. Vertical velocity of this station also clearly shows a reduction of 14 mm/yr. Three-year time series of LAB1 do not show any strange horizontal and vertical motion deviations, but the magnitude of velocity is slower than for the other stations. Therefore, LAWS and LAB1 are discarded in our regional analysis. Directions of four stations on the east side denote slightly bigger SE orientation compared to the stations at the western side. This refers to a different behavior between east and west side of North Borneo. Velocity vectors of BELA and MRDI clearly show the stations are moving away from BIN1, NIAH and MIRI. The region in between appears to be spreading over a relatively short distance of 100 km. In the northern side of Borneo, it is hard to see a similar pattern.

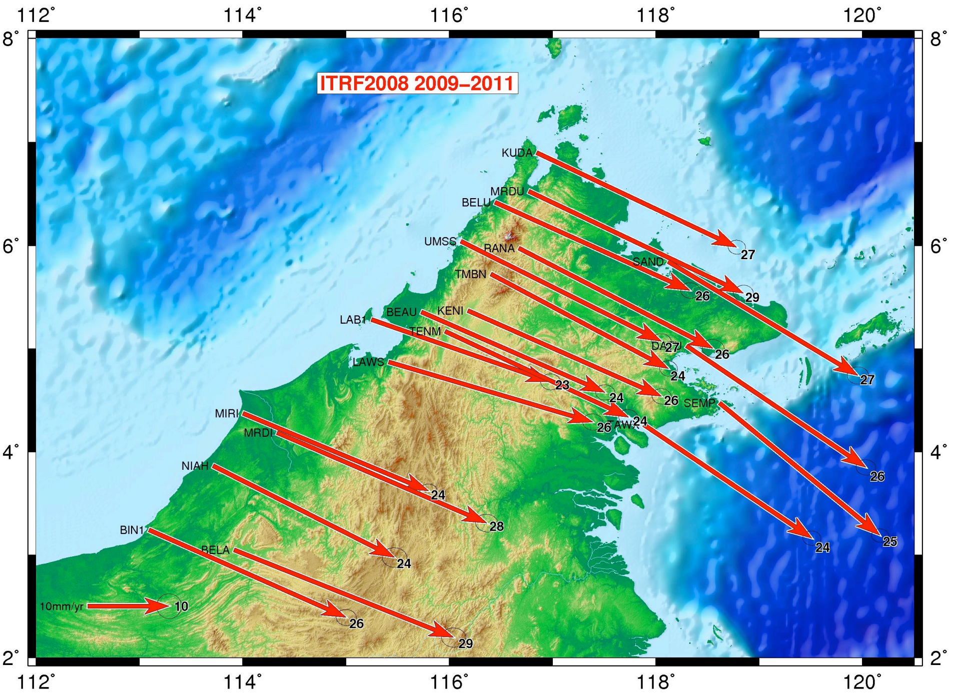

Figure 2: Station velocities in ITRF2008. Error ellipses represent 99% confidence limits.

4.2 Relative Motion with Respect to Sundaland

In order to have a different view of motion patterns, we extracted the Sundaland motion from ITRF2008 velocities by using the Sundaland rotation pole vector solution from Altamimi et al. (2012). This solution used two stations on Sundaland block to estimate the latitude, longitude and anti-clockwise magnitude of Sundaland pole located at 44.243° N, 87.309° W with a 0.388 degree per million-year rotation rate. North Borneo motion overall is a bit slower than estimated as a rigid part of Sundaland, because then the steady-state motion of BEAU should have been 38 mm/yr with direction 121 degrees. Therefore, the direction of residual velocities with respect to Sundaland (Figure 3) is opposite the direction of velocities in ITRF2008 (Figure 2).

On the west side of North Borneo, station motions (BIN1, NIAH, MIRI, BELA and MRDI) show a different angle of spreading in east-west direction but still in a constant direction as visible in their ITRF2008 motion. On the tip of North Borneo, a clockwise rotation can be observed, and these magnitudes are a little bit bigger than calculated by Simons et al. (2007) and used by Sapin et al. (2013). Therefore, it can be concluded that that North Borneo is subjected to a remnant (propagated plate inwards) of convergence between Sundaland and the Philippine Sea plate (~11 cm/yr as given by MORVEL plate model from Demets et al. 2010) that may be higher in the east near the Celebes Sea.

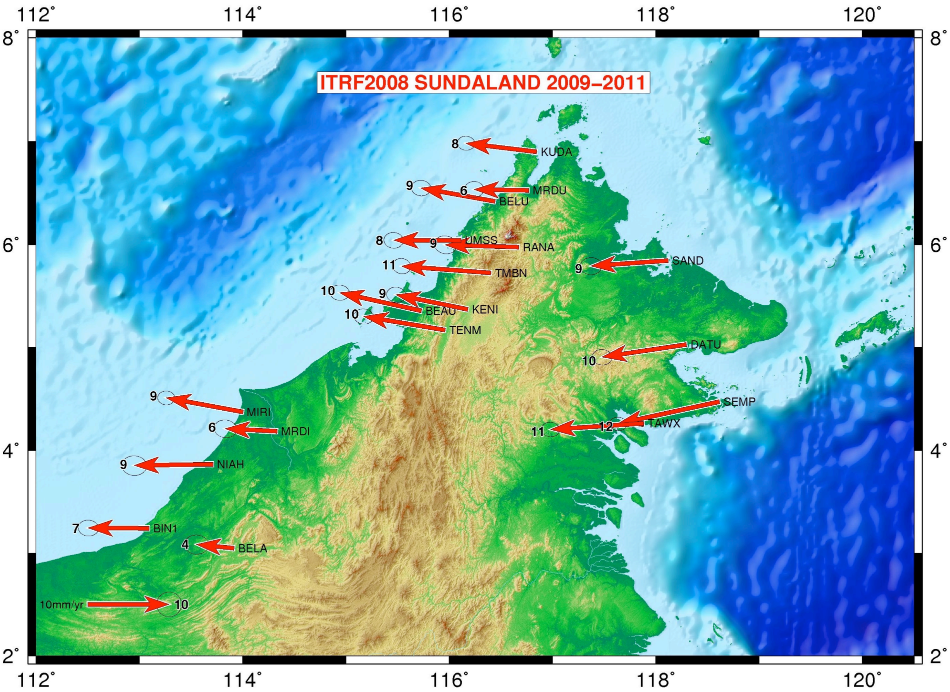

Figure 3: Station velocities respect to Sundaland in ITRF2008. Error ellipses represent 99% confidence limits.

5. BASELINE ANALYSIS IN NORTH BORNEO

The purpose of baseline analysis is to eliminate or reduce seasonal effects and mapping errors. This provides better accuracy of local interaction between stations. For each baseline, daily mapped solutions were used to calculate each baseline. Then, new relative coordinates were obtained by fixing one of the stations. Next weekly average coordinates were used to construct time series for the stations on interest.

5.1 BEAU Fixed Analysis

BEAU station was chosen because this station is located at the most western side and furthest away from the Philippine Sea plate boundary. The east of North Borneo clearly shows relative motions with magnitude between 3 to 6 mm/year towards the south. Therefore, it is hard to see shortening or extension in the east-west direction of North Borneo. SEMP also seems to move ~2 mm/yr faster than the other stations SAND, DATU and TAWX in this region. This could result from elastic loading along a locked fault system (parallel to the coastline in deeper water) that is accommodating differential motions between the eastern part of North Borneo and the Celebes Sea. The west coastal region of North Borneo, also known as North-West Borneo, displays inconsistencies in the station velocities. TENM, KENI, TMBN and BELU all exhibit small relative velocities. MRDU station has a doubtful motion due to vertical trend of up to 10 mm/yr (Figure 6). The other stations (UMSS, RANA and KUDA) have velocities between 2 and 3 mm/yr. Local interaction in North-West Borneo is therefore tough to interpret due to inconsistent directions and magnitudes of the observed relative velocities.

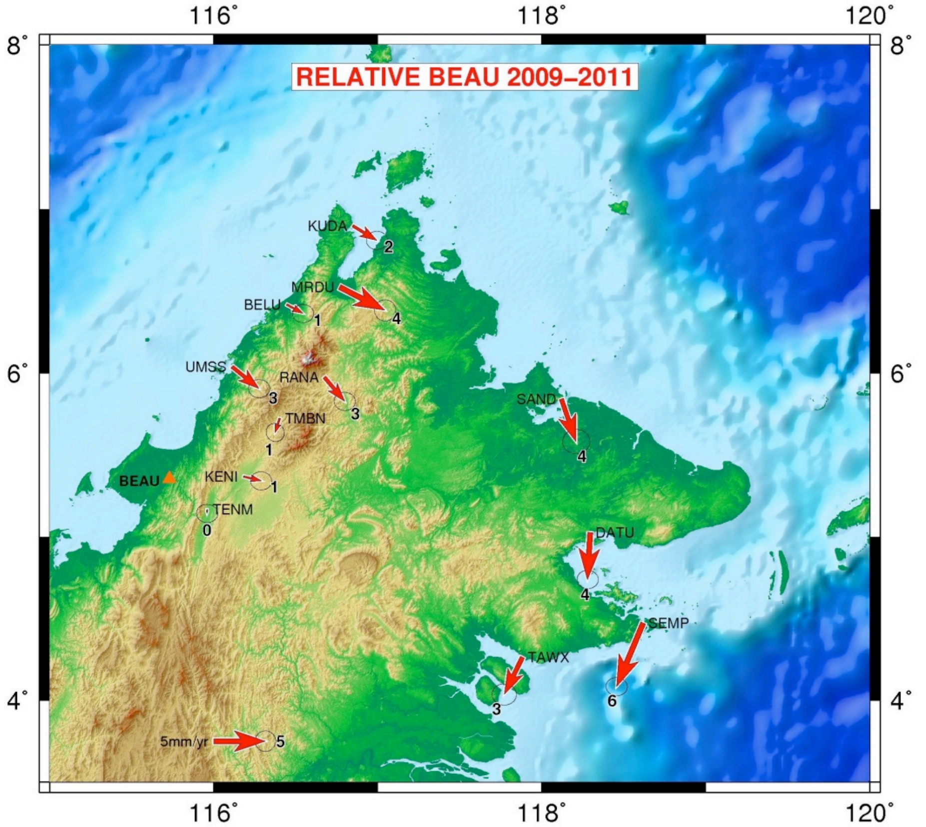

Figure 4: Station velocities with respect to fixed station BEAU (orange triangle). Error ellipses represent 99% confidence limits.

5.2 Coastal Baseline Analysis

Four stations were subsequently selected as fixed points, which are located along the coast to analyze baselines changes along the coastal area of North Borneo. Figure 5 shows inconsistent magnitude and direction of these baseline velocities. MRDI and MIRI are spreading apart at a rate of approximately 3 mm/yr in a direction perpendicular to the shoreline. MIRI station is close to the Baram Delta which is an active gravity-driven fold-and-thrust belt area (Ingram et al., 2004). North-West Borneo is a debated area because here the fold-and-thrust belt appears inactive for a very long time. Many evidences from GPS and offshore seismic measurements indicate the belt is still an active margin (Simons et al. 2007, Sapin et al. 2013, King et al. 2010, Hutchison 2010 and Hesse et al. 2011). The debate is on the source of this active activity. An extension would occur on the coastal area if the activity is driven by gravity. The BEAU-KENI and BEAU-TENM baselines illustrate very small extension in these areas but the UMSS-TMBN baseline suggests compression between these two stations. In the meantime, BELU-RANA baseline displays an extension 2 mm/yr towards south. However, this analysis totally depends on the fixed stations, which may be affected by unknown small local motions that may not be necessarily due to geophysical processes.

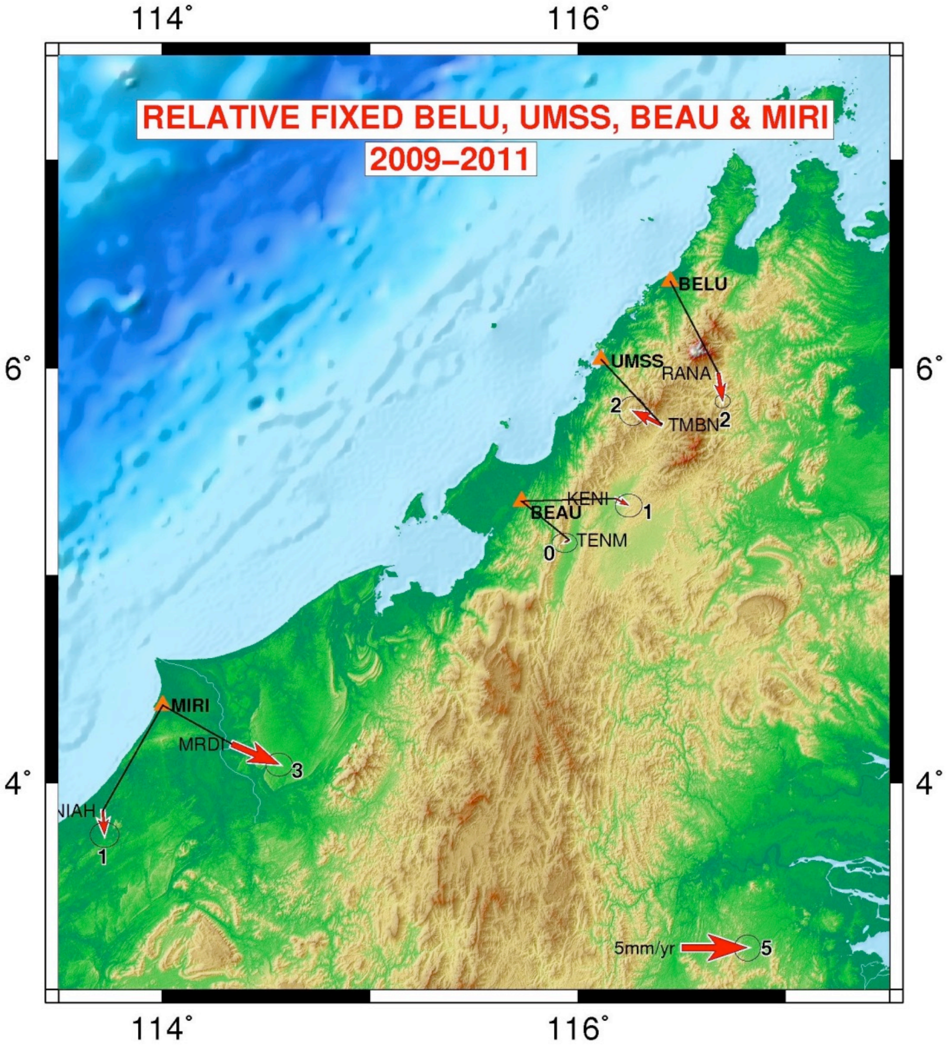

Figure 5: Coastal baseline changes with fixed stations MIRI, BEAU, UMSS and BELU. Error ellipses represent 99% confidence limits.

6. VERTICAL MOTION IN NORTH BORNEO

Vertical motions of North-West Borneo show trends ranging from 0±2 to 10.8±1.5 mm/year (99% confidence error level). MRDU seems to have local subsidence up to almost 11 mm/yr. Other stations indicate declination from -1.3 to -3.4 mm/year except RANA. RANA seems to behave differently than the other stations. Figure 1 shows RANA station is surrounded by a few active faults. In addition, RANA is the closest station to Mount Kinabalu but not on high altitude area. Nevertheless, most standard deviations of the trend are bigger than the estimated trends. Therefore still more data is needed to achieve more reliable estimates on the possible vertical motions in this region.

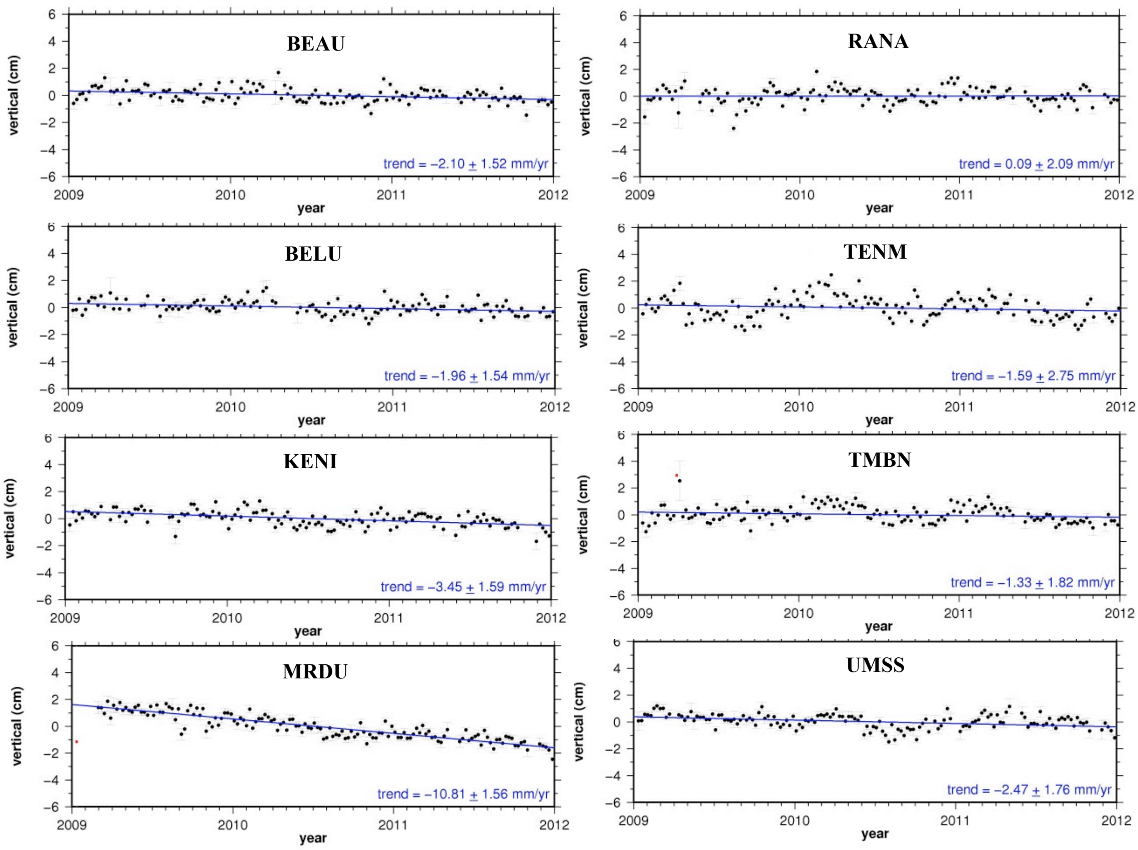

Figure 6: Vertical position time series in North-West Borneo (99% confidence level)

7. CONCLUSION

The stations (MIRI and MRDI) close to Baram Delta indicate an extension rate of 3 mm/yr over a distance of 40 km. This visible extension may be due to gravity sliding activity in the Baram Delta. However GNSS stations in North-West Borneo do not show significant extension or compression. Results might also be affected by local or individual motions of some stations. Therefore, our ongoing study of the deformation in North Borneo still requires further extension of the position time series to investigate any small deformation signals and obtain reliable results. Other geodetic techniques (like Interferometric Synthetic Aperture Radar (InSAR)) may also be useful to support results from GNSS. In a future study, any actual rotation of North Borneo with respect to Sundaland will be also deducted as the residual motions might give a better insight in the ongoing deformations of North-West Borneo. Detailed information of geological setting in Borneo is needed to estimate boundary of North Borneo block if it indeed can be quantified as an independent micro block or instead the deformation pattern results from different elastic loading deformation patterns due to remant Sundaland-Phillipine Sea plates convergence that is accomodated in and along North-West Borneo.

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