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GEOLOGICAL MAPPING OF SABAH, MALAYSIA, USING AIRBORNE GRAVITY SURVEY

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ABSTRACT. Airborne gravimetry is an effective tool for mapping local gravity fields using a combination of airborne sensors, aircraft and positioning systems. It is suitable for gravity surveys over difficult terrains and areas mixed with land and ocean. This paper describes the geological mapping of Sabah using airborne gravity surveys. Airborne gravity data over land areas of Sabah has been combined with the marine airborne gravity data to provide a seamless land-to-sea gravity field coverage in order to produce the geological mapping. Free-air and Bouguer anomaly maps (density 2.67 g/cm^3) have been derived from the airborne data both as simple ad-hoc plots (at aircraft altitude), and as final plots from the downward continued airborne data, processed as part of the geoids determination. Data are gridded at 0.025 degree spacing which is about 2.7 km and the data resolution of the filtered airborne gravity data were 5-6 km. The airborne gravity survey database for land and marine areas has been compiled using ArcGIS geodatabase format in order to produce the update geological map of Sabah.

KEYWORDS. Airborne gravimetry, gravity field, ArcGIS, geological mapping,

INTRODUCTION

Airborne gravimetry is an effective tool for mapping local gravity fields using a combination of airborne sensors, aircraft and positioning systems. It is suitable for gravity surveys over difficult terrains and areas mixed with land and ocean. The development of airborne gravimetry has been made possible by the use of the kinematic Global Positioning System (GPS) technique as well as improvement in airborne gravity acceleration sensor system. Major advances in airborne scalar gravimetry as a production system and with its detailed error models have made it possible to use airborne gravimetry as a relatively standard technique in geodesy/geophysics, with best accuracies independently at 1-2 mGal at 5 km resolution for fixed-wing aircraft (Forsberg et al, 1999 and Olesen & Forsberg, 2007).

This paper describes some recent (2014-2015) airborne gravity surveys undertaken by Jabatan Ukur Dan Pemetaan Malaysia (JUPEM) under the Marine Geodetic Infrastructures In Malaysian Waters (MAGIC) Project over marine areas in Sabah (JUPEM, 2014/2015). Airborne gravity data from previous field campaign carried out in 2002-2003 over land area in Sabah has been combined with the present marine airborne gravity data to provide a seamless land-to-sea gravity field coverage (JUPEM, 2003). The airborne gravity survey database for land and marine areas of Sabah is considered complete and has been compiled in ArcGIS geodatabase format. Some geological inferences also been presented to initiate further research on the application of gravity field in marine geology and geophysics.

METHODOLOGY

The Principle of Airborne Gravimetry

The basic principle of airborne gravity measurement from a damped two axes platform gravimeter is depicted in Figure 1. The total acceleration g^* at a point in the airplane is measured by a modified marine gravimeter and a high performance inertial-grade accelerometer triad. The total acceleration is composed of the earth's gravity field g and accelerations a related to the motion of the airplane relative to the earth's surface. Given the position of the airplane to any instant, it is possible to compute the acceleration a , and thereby the gravity field g at all positions. The position of the airplane is obtained by kinematic carrier- phase differential GPS, where the combined observations from GPS receivers in the airplane and from a reference station in the area of interest, makes it possible to estimate the instantaneous position of the airplane with the required precision.

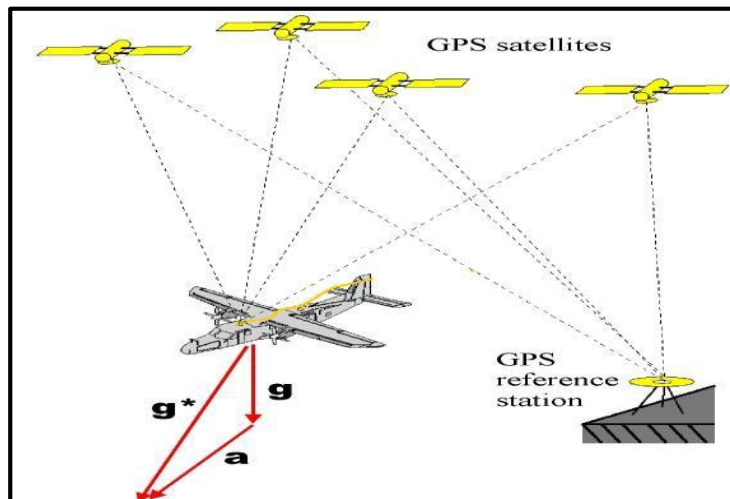


Figure 1. Principle of airborne gravimetry.

Gravity Equations Relevant To Stabilized Platform Systems

The principle of airborne gravimetry is to measure the total acceleration by a gravimeter, and subtract the non-gravitational accelerations as determined by GPS and inertial measurement unit (IMU). The fundamental equation for the free-air gravity anomaly, $\Delta g(\varphi, \lambda, h)$, from relative airborne gravity measurement can be derived as follows (Forsberg, 2010):

$$g(\varphi, \lambda, h) = f_z - \ddot{h} - \delta g_{Eotvos} - \delta g_{tilt} - f_{z_0} + g_0$$

$$\Delta g(\varphi, \lambda, h) = g(\varphi, \lambda, h) - \gamma_0 + 0.30877(1 - 0.00242 \sin^2 \varphi)(h - N_{EGM}) + 0.75 \times 10^{-7}(h - N_{EGM})^2$$

Where:

$g(\varphi, \lambda, h)$:	gravity value at aircraft altitude (mGal),
f_z	:	airborne gravimeter reading (mGal),
\ddot{h}	:	GPS acceleration (mGal),
δg_{Eotvos}	:	full ellipsoidal Eotvos correction (mGal),
δg_{tilt}	:	tilt correction (mGal),
f_{z_0}	:	gravimeter base reading (mGal),
g_0	:	apron gravity value (mGal),
γ_0	:	normal gravity on the ellipsoid (mGal),
h	:	GPS ellipsoidal height of aircraft (m), and
N_{EGM}	:	geoid height from Earth Gravity Model (EGM) (m).

Airborne Gravity Survey Equipment and Choice of Aircraft

The present project make use of a stabilized two axes platform system comprises of the LaCoste & Romberg (LCR S-99) Air-Sea gravimeter and iMAR strap-down Inertial Measurement Unit (iMAR-IMU) (Figure 2). This airborne gravimetry configuration combines two measurement systems to estimate the gravity field. Total acceleration of the aircraft is measured by a gravimeter, or an IMU. Accelerations due to the movement of the aircraft are measured with signals from dual frequency GPS receivers. The difference of these two acceleration measurements is the effect of the gravity field. As the aircraft travels, a time series of geo-referenced gravity can be estimate. Lower flight speeds lead to higher resolution gravity field estimates. Herein, resolution is defined as the minimum recoverable half wavelength. To minimize attenuation of the gravity signal, flight heights are kept low as well.

The most important criteria for aircraft selection is the good auto-pilot and low phugoid dynamics. The Beech King Air BE200 (9M-KNS) from Sabah Air Aviation Sdn. Bhd. has been tested extensively during the 2014-2015 MAGIC campaign and has proven to be suitable for airborne gravity and magnetic data acquisition (Figure 3).



Figure 2. The Imar-IMU unit and LCR S-99 gravimeter.



Figure 3: Sabah Air BE200 aircraft.

Airborne Gravity Survey in East Malaysia

The Airborne gravity survey undertaken by JUPEM covered over land and territorial waters (up to 12 nautical miles) the flight line spacing is maintained at 5 km, while beyond the territorial waters (> 12 nautical mile) the flight line spacing is at 10 km. The aircraft altitude is maintained at 2000 m wherever possible with a flight speed of 300 km/hr.

Aero-Gravity Data Processing

There are two main parts in the processing of airborne gravity data. The first is to separate gravitational accelerations (f_z) from kinematics aircraft accelerations (\ddot{h}). This separation process will mainly impact the resolution of the system. A proper separation of gravitational and kinematic accelerations requires a good description of the gravity sensor response. The sensor modelling developed by Denmark Technical University (DTU-Space) appears to exploit most of the potential of the gravity sensor used in this project, i.e., the LaCoste & Romberg S- gravimeter. GPS related errors will also impact the separation of accelerations and routines to identify and model such errors have been developed and implemented in this project.

The second parts is in airborne gravity processing is to keep track of the orientation of the sensors during the flight. This is crucial to the recovery of the longer wavelengths of the gravity field, and hence for geodetic use of the data. A new algorithm for airborne gravity processing that addresses the misalignment or off-level problem has been developed by DTU (Olesen, 2003). This new approach yield almost bias free data. The near bias free nature of the data from the DTU processing system is the underlying fact that no crossover adjustment procedures are necessary in the data reduction. The standard procedures for the airborne gravity processing can be described as in Figure 4:

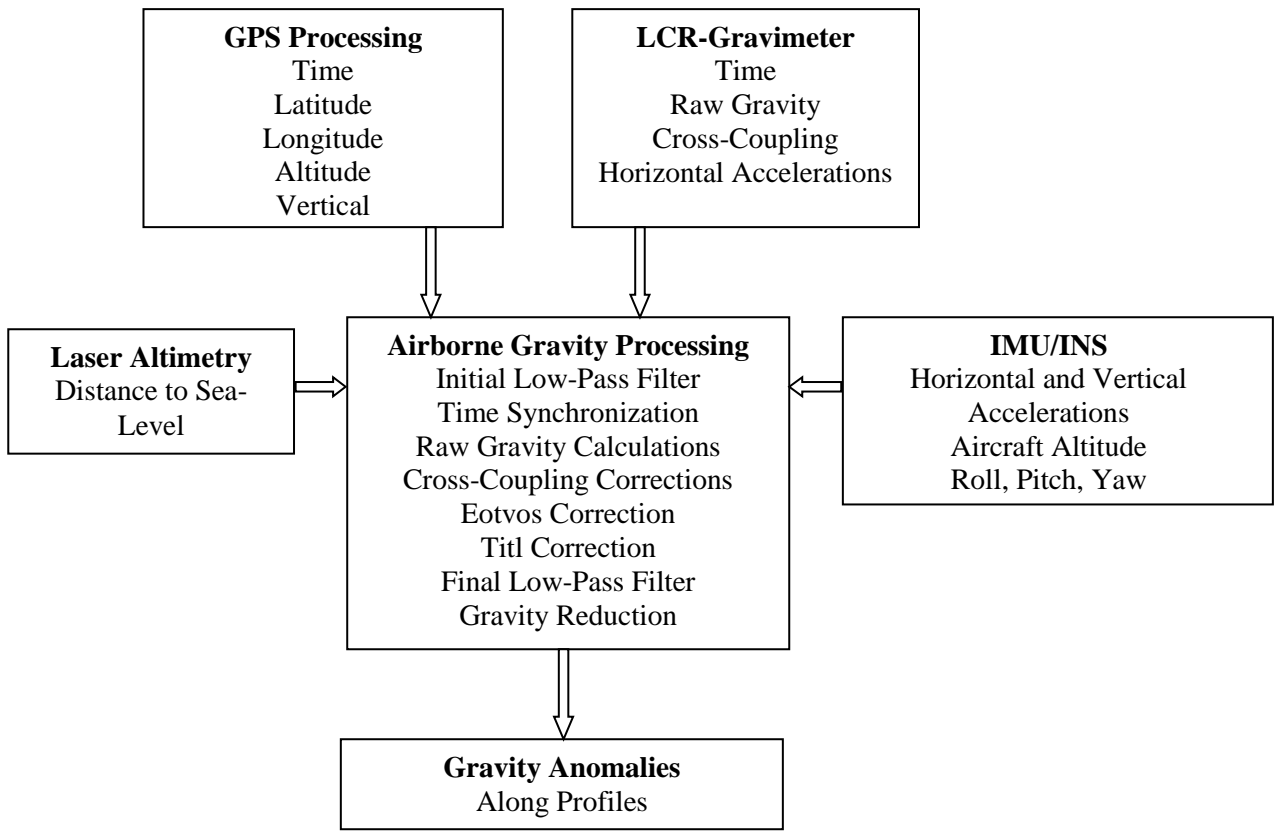


Figure 4: Airborne gravity data processing flowchart: Overview on input data, processing step and output data. Input from laser altimetry is optional (Adapted from Alberts et al, 2007)

Because of the potential for high amplitude in the horizontal accelerations, and the small differences between accelerations from accelerometer and GPS measurements, the computed tilt effect is quite sensitive to the numerical treatment of the data (Olesen, 2003 & Forsberg et al, 1999). Calibration factors for the accelerometers have been determined by a Fast Fourier Transform (FFT) technique, based on the frequency dependent behaviour of the platform, and similar method has also been used for the calibration of the dynamic beam scale factor (Forsberg et al, 1999).

Apron reference gravity values have been determined by relative gravity measurements to the JUPEM’s gravity reference stations, which is given in the International Gravity Standardization Network 1971 (IGSN71) system. The apron reference values are located at the aircraft parking area and need to be corrected for the height of the aircraft (Table 1). A number of the gravity base readings to the airborne gravity system have to be made during the field campaign period to ensure attainment of a smooth drift function of the airborne gravimeter.

Table 1: Gravity Base Station Values

Station	Coordinates (WGS84)		Gravity (mGal)	Sigma (mGal)	Year
	Latitude	Longitude			
Kota Kinabalu Airport.	5° 56' 25.71"	116° 03' 2.23"	978112.982	0.030	2014
Sandakan Airport, BE200 Hanger	5° 53' 55.05"	118° 38' 25.22"	978078.457	0.037	2015

Filtering of Airborne Gravity

It should be pointed out that no bias adjustment on a line- by-line basis is done on the final aero-gravity data; the absolute level of the gravity line data is determined by a smoothly varying base reading curve. The aero-gravity equation is filtered with a nominal 150 sec triple-stage zero-phase forward/backward Butterworth filter, giving a resolution of about 5-7 km for the final gravity free-air anomaly data, depending on aircraft ground speed (Figure 5).

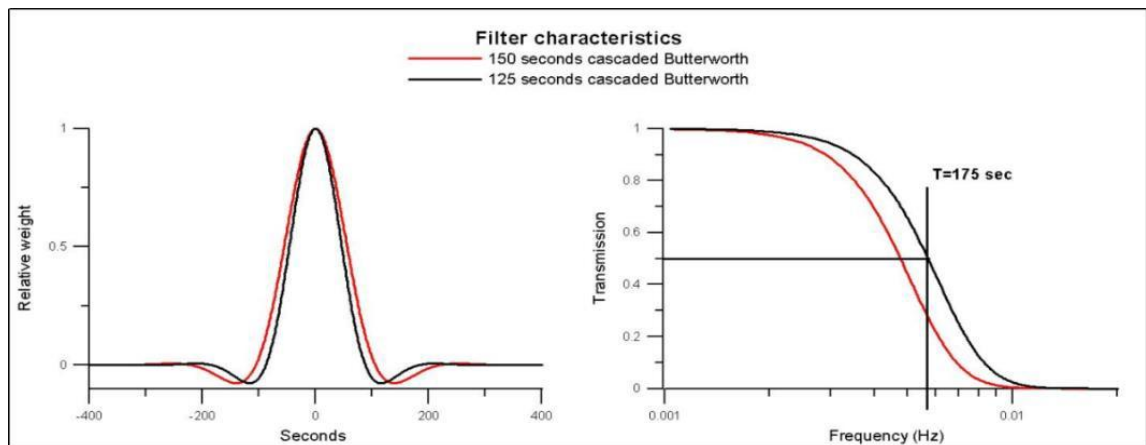


Figure 5. Impulse response (normalized) and spectral representation of the two different low pass filters used in the airborne gravity processing (Forsberg, 2010)

Crossover Analysis

An analysis of the misfit in the crossing points will indicate the crossover difference (RMS) Table 2 presents the results of cross-over analysis for airborne survey campaign of 2002- 2003, 2014 and 2015. It should be emphasized that no sort of bias adjustment will be applied to the data in order to reduce the misfit in the line crossings. This crossover error will indicates the noise level on the data (un-modelled errors), assuming the noise to be uncorrelated from track to track.

Table 2. Cross over analysis of the airborne survey campaigns in East Malaysia

Year	R.M.S. Crossing	Max	Line Error Estimate	Cross-Over Points
2002-2003	3.2	n/a	2.2	n/a
2014	3.0	9.0	2.1	72
2015	2.6	7.1	1.8	146

The cross over analysis also been carried out from inter-comparison of the 2002-2003 Sabah airborne gravity and the 2015 airborne gravity survey. This comparison was done with *geogrid* in the DTU GRAVSOF software package, for points within 1 km distance, but separated in height. The comparison showed a result consistent with error estimate, with a mean of 1.0 mGal and r.m.s. difference of 2.4 mGal for 394 cross-points (Figure 6).

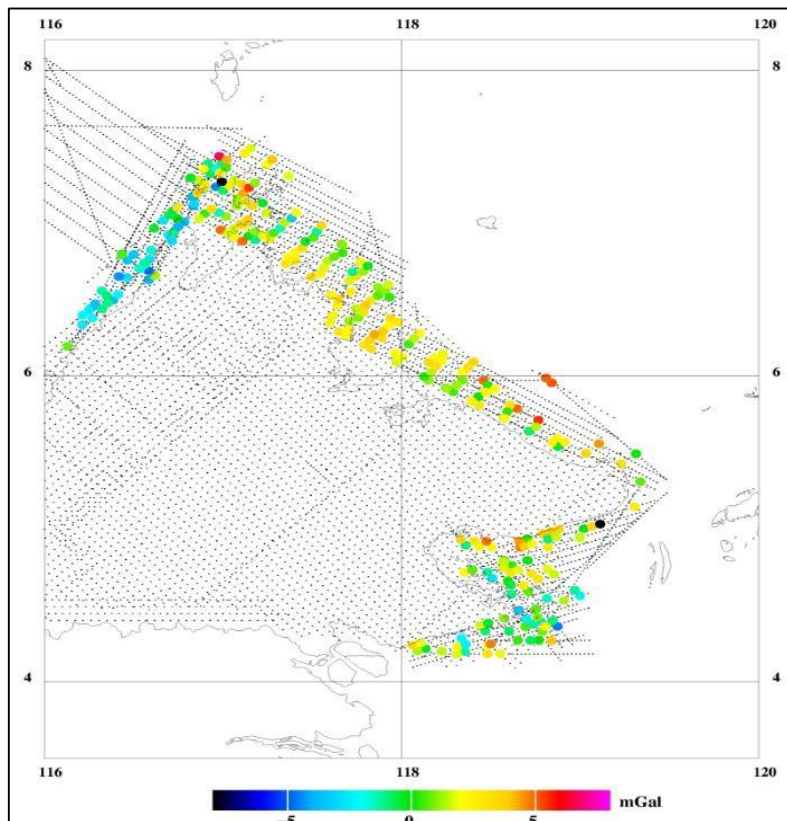


Figure 6. Cross-over errors of 2015 airborne gravity versus 2002-2003 survey. Flight heights may differ up to 2 km or more.

Downward Continuation of Airborne Gravity Data

Downward continuation is necessary to reduce the airborne data from the flight level to the terrain (Forsberg, 2002). Since gravity data both exist on the terrain and at altitude, and since the flights will be at different altitudes, the method of least squares collocation is used (Hofmann-Wellenhof & Moritz, 2006). The downward continuation of airborne gravity and the gridding of data, have been performed using block-wise least-squares collocation, as implemented in the *gpcoll* module of GRAVSOF (DTU, 2014). This module uses a planar logarithmic covariance function, fitted to the reduced data.

RESULT AND DISCUSSION

Free Air And Bouguer Gravity Anomaly Fields

The airborne gravity survey database for land and marine areas of Sabah were compiled using ArcGIS geodatabase format. Free-air and Bouguer anomaly maps (density 2.67 g/cm^3) have been derived from the airborne data both as simple ad-hoc plots (at aircraft altitude), and as final plots from the downward continued airborne data, processed as part of the geoid determination. Data are gridded at 0.025 degree spacing ($\sim 2.7 \text{ km}$). Data resolution of the filtered airborne gravity data are 5-6 km, depending of aircraft speed. Both Free-air and Bouguer anomalies has been reduced for residual terrain model (RTM) relative to a mean elevation surface. The overall results of the airborne survey are consistent and of high accuracy.

Geological Mapping

The geological maps of Sabah Malaysia are given in Figure 7. The map indicates the rock distribution and age of rock formations in Sabah. However, there is no available data for the rock formation in the offshore areas.

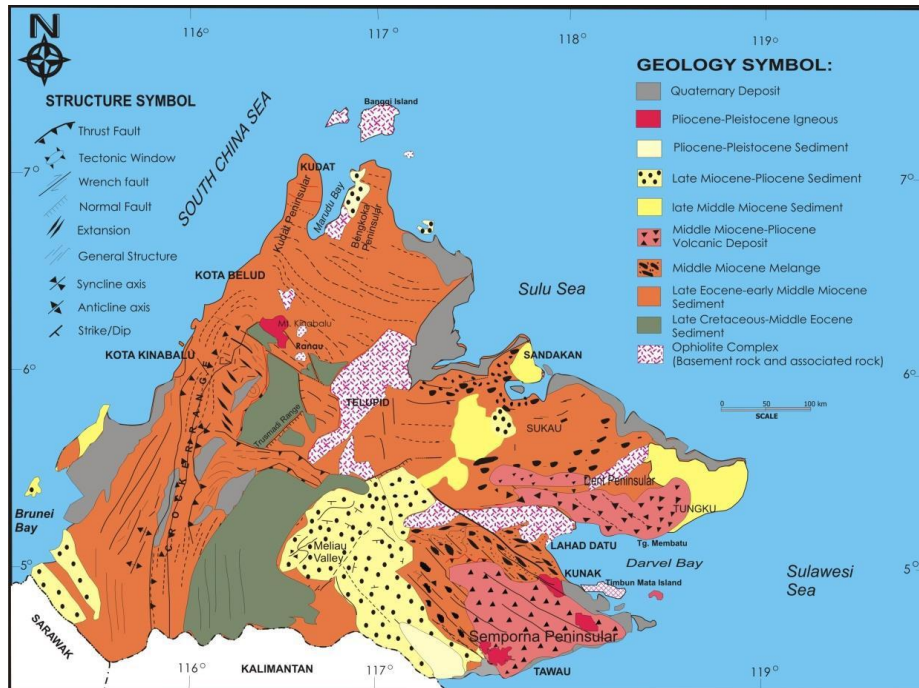


Figure 7. Geological mapping of Sabah, Malaysia (Modified from Yin,1985)

Therefore, the Bouguer gravity anomaly is very significant data in order to extend the rock formation to the marine areas. The gravity anomaly data also can be used to interpolate the rock formation in the remote areas. Bouguer gravity anomaly in the Darvel Bay area extending to Mount Silam and Segama Valley in Lahad Datu area shows high positive anomalies of 60-140 mGal (Figure 8). The association of Pre-Tertiary mafic and ultramafic rocks exposed at Darvel Bay, is believed to form an ophiolite suite (Dwayne, 1986), may result in the large positive anomaly detected from the airborne gravity survey.

The Semporna Peninsula also indicates a high Bouguer anomaly of 40-80 mGal. The Tawau Mountains, the Neogene-Quaternary volcanic remnants, form the prominent feature of the Semporna Peninsula. Volcanic rocks of the andesite-dacite basalt association are forming the major mountainous backbone of the area. The Semporna Peninsula Middle Miocene paleo- magmatic arc was represented by volcanic rocks associated with sedimentary rocks deposited in a shallow marine environment (Sanudin et al, 2010).

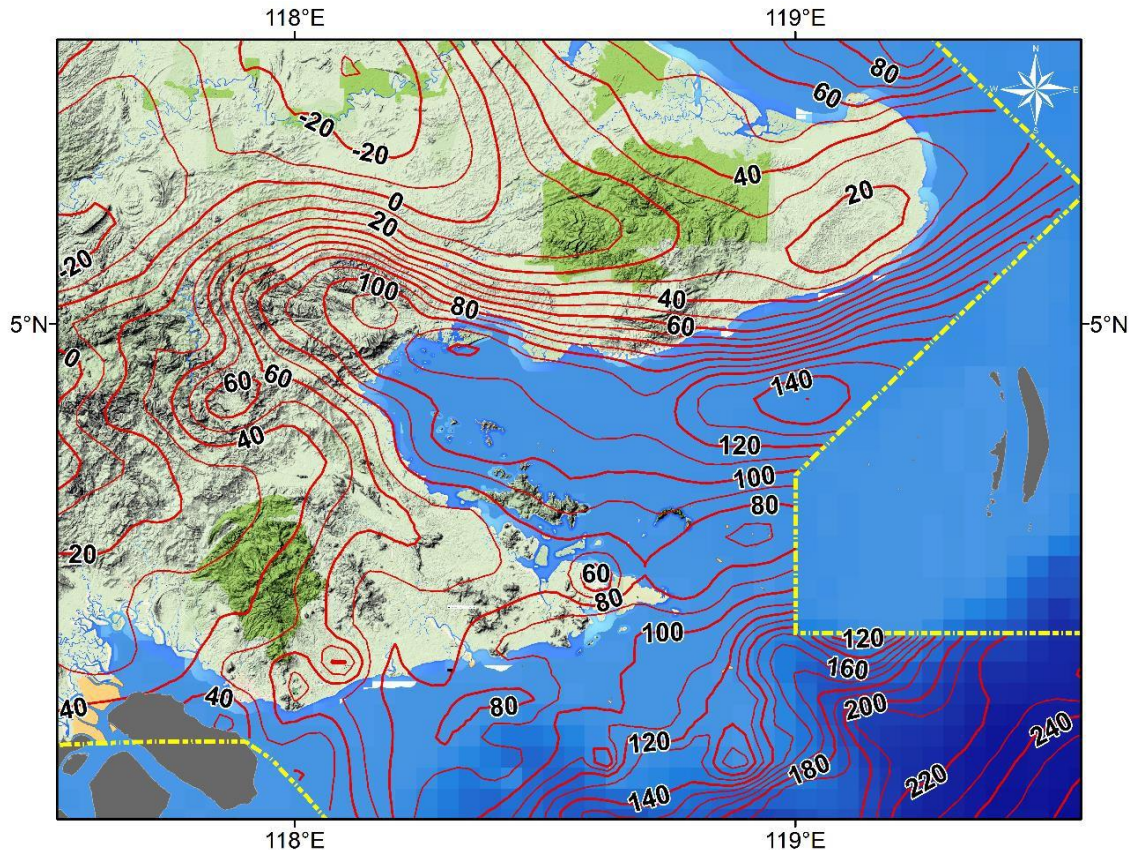


Figure 8. Bouguer gravity anomaly map in the Darvel Bay, Dent Peninsula and Semporna Peninsula (contour interval = 10 mGal) (Background base map is taken from Google Terrain)

In order to understand the source of high gravity anomaly in the Darvel Bay, we have extended the gravity anomaly map to cover the Eastern and Northern Sabah including part of the Sulu Sea. Since airborne gravity data is available only inside Sabah territory, the airborne Free-air gravity anomaly has been combined with DTU10 Free-air gravity anomaly derived from satellite altimetry (Anderson, 2010) for areas outside Sabah territory. The resulted Free-air anomaly field is shown in Figure 9. The Free-air gravity maps clearly indicate high gravity anomaly (+50 to +100 mGal) over the Banggi-Palawan Ridge in the Northern Sabah and over the Sulu-Darvel Bay Ridge in Eastern Sabah. The two high positive Free-air gravity anomaly belts are separated by a low (- 20 mGal) gravity anomaly cantered at the Bukit Garam Basin area.

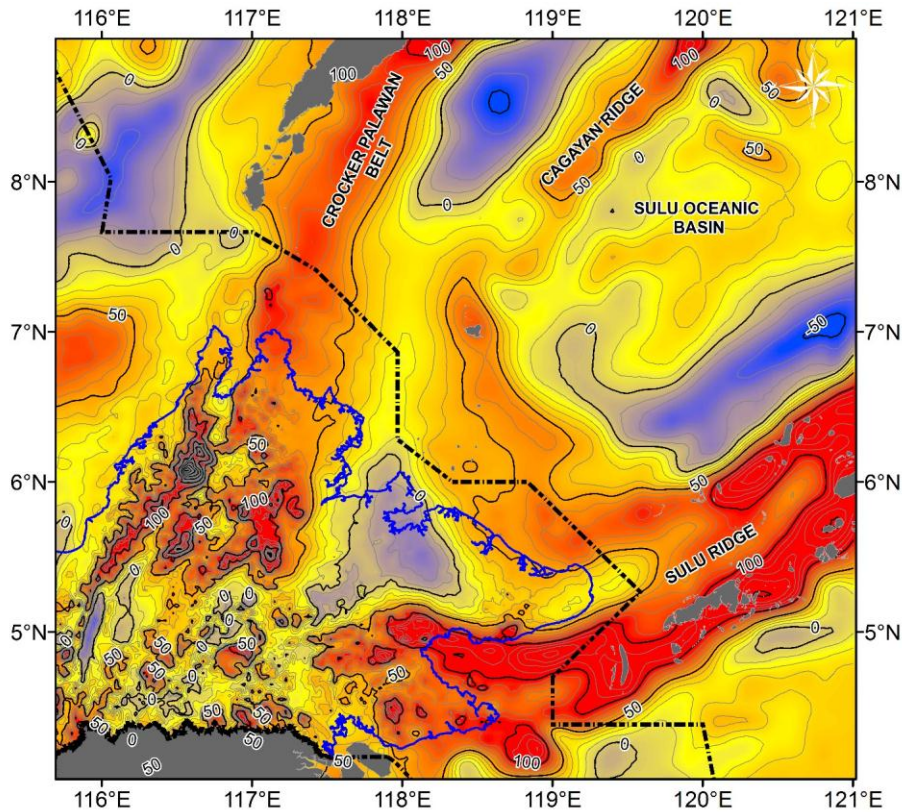


Figure 9. Free-air gravity anomaly map in the north-eastern Sabah combining airborne gravity (inside Sabah territory) and DTU10 satellite altimetry (Anderson, 2010) (outside Sabah territory) (contour interval = 10 mGal)

Also clear from Figure 9 that the Banggi-Palawan Ridge and Darvel Bay-Sulu Ridge extended on land into Sabah giving rise to high positive gravity anomaly on land near Telupid (+100mGal) and Lahad Datu area (+100 mGal), respectively. Similar high gravity anomaly patterns also is clearly seen in Bouguer anomaly map. Hutchinson (1992) also presented some findings on the extension of the Sulu and Cagayan oceanic ridges on land into Sabah. However, it is not clear from Figure 9 on the intrusion of Cagayan Ridge into Sabah.

The Free-air gravity anomaly map (Figure 9) shows basic patterns which correlate the major geologic characteristics of Sabah. High gravity anomalies (+50 to +100 mGal) dominate the western and eastern part of Sabah running NE – SW trend separated by low (-20 mGal) gravity centred at Kinabatangan District. This high anomaly (+100 mGals) runs almost in a parallel trend from Palawan ridge in the Philippines southward to Bengkoka Peninsula in Sabah and finally ended up at the southern tip of the Crocker Range, west Sabah. Equivalent trend of highest value in Sabah exceeding +140 mGals, can be observed from Danum Valley, curving towards east, passing through Darvel Bay and finally joining the Sulu Ridge in the Philippines. The ground evidence of the characterised anomalies is the manifestation of the

Cretaceous oceanic crust that fragmented and uptrusted during the Middle Miocene. The rock unit is classified as the Chert Spilite Formation or generally called ophiolitic basement of Sabah, dominated by basalt and ultrabasic rocks. This Free-air gravity anomaly correspond to the Bouguer gravity anomaly in the Darvel Bay and Semporna Peninsula areas and extending to Segama Valley in Danum Valley shows high positive anomalies of 60-140 mGal (Figure 8). The high anomalies (+100 mGals) aligned with the thick Paleogene sedimentary sequences in the western part of Sabah, the Crocker Formation and the Trusmadi Formation could be the manifestation of the up trusted Cretaceous oceanic crust (ophiolitic rock) concealed below the thick sedimentary sequence.

Equivalent anomalies trending almost east-west running parallel to the general framework of the Dent and the Semporna peninsulas clearly show the distribution of Middle Miocene to Quaternary volcanisms. The distribution of the highest anomalies of the regions is clearly locate the mountain ranges consisting of three isolated peaks; namely Magdalena, Wullersdorf and Pock in Semporna Peninsula and the Bagahak Range in Dent Peninsula. The volcanic sequence that formed the mountain chain of Semporna Peninsula contributes thick pyroclastic apron and lava flows of andesitic, dacitic and basaltic rock types. These volcanic rocks are underlain by the Middle Miocene volcanoclastic sequence, the Kalumpang Formation. Pock, Wullersdorf and Magdalena mountains form the major topographic features of the Semporna Peninsula (Sanudin et.al., 2010). The youngest volcanic aprons covering an extensive area overlying the older volcanic rocks erupted around the late Pleistocene time, the olivine basalt. These volcanic associations stratigraphically superimposed and form important link with the long chain of the Tertiary volcanic activities in this region that extend from the Sulu Archipelago, Philippines to this part of Sabah (Sanudin & Baba, 2007).

The negative anomalies in Kinabatangan District and the surrounding areas divide the two highs that can be accounted for almost entirely by the existence of low density roots for the crust that support thick pervasively loose sediment of the region, originally formed by huge pressurised mud diapirism currently exposed as the Garinono Formation (Diapiric Melange). This rock unit is part of the Middle Miocene stratigraphic unit of Sabah (Sanudin & Baba, 2007). Other Miocene rock units of the valley and ridges are characterised by -20 to -40 mGals anomalies with some moderate variations.

Pensiangan – Kalabakan area includes Maliau Basin are the areas with Free-air anomalies averaged about zero but show a wide range from -20 mGals to +50 mGals. The positive anomalies occur in the form of irregular spaced knobs on ridges, while the negative anomalies are the smoother intervening depressions which tend to be aligned along the northeastern of Sabah. Another set of prominent knobs are scattered in a tangle manner, divided by irregular depressions in between. The Free-air anomalies of those exceeds +50 mGals, are most likely due to the occurrence of dense basic rock types (like basalt and ultrabasic rocks) scattered as blocks in the Middle Miocene melange. The Late Miocene sediment of the region is in a form of apron that blanketed the Middle Miocene melange beneath. Most of the prominent knobs show steep anomalies indicating a possible dip

of the structures of the area. Sedimentary lows on the western part running NE- SW trend are related to the increased thickness of Quaternary sedimentary deposits. However, the young deposits exposed all over Sabah do not significantly affect the gravity anomalies since they have uniform or only gradually varying thickness.

CONCLUSIONS

The present airborne gravity survey make use of a stabilized two axes platform system comprises of the LaCoste & Romberg (LCR S-99) air-sea gravimeter and iMAR strap-down inertial measurement unit (iMAR-IMU). This airborne gravimetry configuration combines two measurement systems to estimate the gravity field. Total acceleration of the aircraft is measured by a gravimeter, or an IMU. Accelerations due to the movement of the aircraft are measured with signals from dual frequency GPS receivers. This combination proved to be a very reliable concept for acquiring quality gravity data for geological mapping. The airborne gravity survey database for land and marine areas of Sabah is considered complete and has been compiled in ArcGIS geodatabase format. Some geological inferences also been presented to initiate further research on the application of gravity field in marine geology and geophysics in Sabah, Malaysia.

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