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Subsurface Fault Mapping of Central Luconia Province, Offshore Sarawak through Airborne Full Tensor Gradiometry (Air-FTG®) Interpretation

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Abstract

This study aims to delineate different structural trends at different depth ranges in Central Luconia, offshore Sarawak by utilizing the depth (Z) component from the airborne gravity. Different wavelengths range applied on the gravity data allows estimation of different depth in the subsurface, thus providing tools for detailed fault mapping in this area. Very short wavelength data include Contact Lineament Processed data at 5-20 km yield NE-SW oriented faults that stand-alone from the other gravity anomalies maps interpreted. This is assumed to be related to recent gravitational tectonic that impacted this area. Short wavelength Tzz to intermediate wavelength Txz and Tyz, as well as long wavelength CLP data possesses dominant NW-SE trend. It is interpreted to follow the major NW-SE orientation of West Baram and West Balingian Lines that bounded Central Luconia. An E-W orientation is detected in the deep subsurface (long wavelength) and has possibility to reflect the orientation of the basement. Comparison of gravity anomaly with existing location of carbonate build-ups reveal most of carbonate in Central Luconia grow in low gravity areas and exhibit smaller size build-ups compared to the build-ups in West Luconia that have bigger size and grow on high positive gravity areas. An obvious circular structure with low gravity response in Central Luconia is further evaluated with existing exploration wells nearby and it is suggested for further evaluation for potential hydrocarbon exploration area in Central Luconia.

***Keywords**: Full tensor gradiometry gravity; Airborne gravity; Fault interpretation; Subsurface interpretation; Central Luconia; Carbonate and gravity.*

1. Introduction

Airborne Full Tensor Gradiometry (Air-FTG®) is a multiple accelerometer moving platform technology that measures the accelerations in the inline and cross signals from the three Gravity Gradient Instruments (GGI) which are converted to directional gradients to provide tensor elements of Tyx, Tyy, Tyz, Txz and Tzz tensor components [1], along with another four combination tensors (Figure 1a). The different tensor components in Air-FTG® are commonly used to recognize and classify different lineaments associated with structural and/or stratigraphic changes, based on contrasting frequency slicing, that represent different scale and target depth of the geological structures. Air-FTG® provides better resolution especially at the shallower subsurface compared to satellite gravity (Figure 1b).

Air-FTG® was successfully acquired in Central Luconia Province, offshore Sarawak (Figure 2) by Bell Geospace Limited (BGL) in 2014. Central Luconia Province is located on continental crust that overloaded with thick sedimentary sequences comprising various siliciclastic rocks and limestone. The usage of Air-FTG® in this area is highly suitable because of the density contrasts between the carbonate rocks with other siliciclastic rocks (shale, claystone and sandstone) as well as the crystalline basement underlying the basin. With the advantages of having different tensor components from the Air-FTG®, this study aims to re-access the structural orientation observed from depth (Z) component of the airborne gravity data within Central Luconia and evaluating the effects of these faults for the growth of Miocene carbonate in Central Luconia Province.

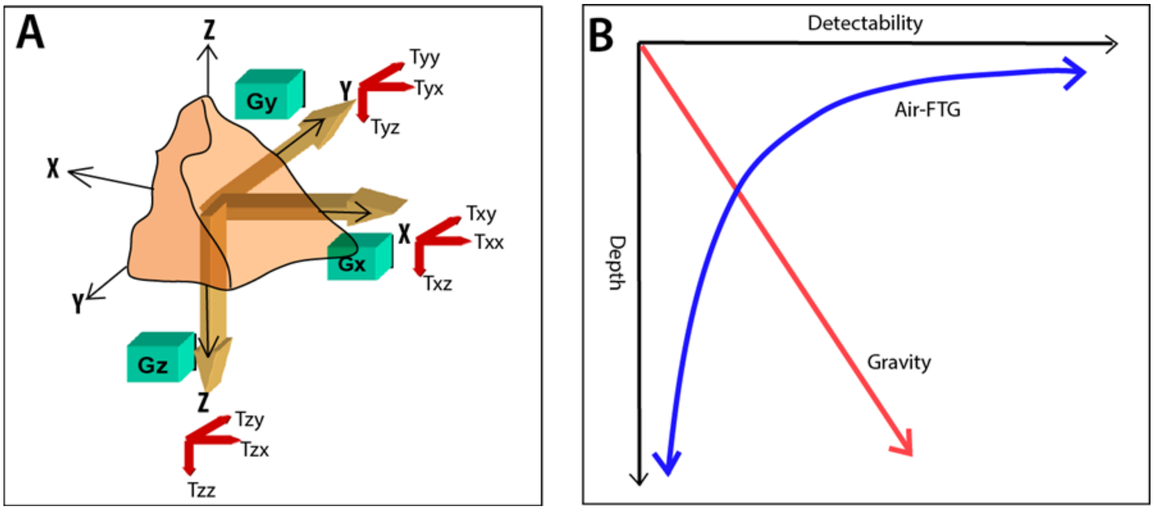

Figure 1. A) The tensor components from Air-FTG® data edited from [1]. In this study, only Z-gradient (Gz or Tz) is utilized which include the Txz, Tyz, and Tzz along with Contact Lineament Processed (CLP) from Tz. B) General concept of efficiency in detecting density contrast in the subsurface between airborne gravity and conventional gravity data over depth

2. Geological setting

Central Luconia Province in offshore Sarawak, Malaysia is prolific hydrocarbon exploration sites for more than 50 years ago [2], mainly from the dominant carbonate reservoirs of Middle to Upper Miocene age. Central Luconia is dominated by thick sedimentary rocks dated from the Oligocene to present day. The formations of sediments in this area is locally known as Cycles, representing the relation of sediments deposition with global sea level changes [3], with Cycle I being the oldest sediments and Cycle VIII is the youngest (present-day) sedimentation. The exploration of oil & gas in Central Luconia usually emanates from Cycle IV and V carbonate build-ups and new hydrocarbon targets within the Cycle II and III sediments are being explored [2;4].

Central Luconia is bounded by two main tectonic faults notably known as West Baram Line in the east and West Balingian Line in the west (Figure 2). It is well known that basins in Central Luconia Province deposited on top of continental crust (Luconia Shelf) that was drifted from the southern China in Eocene-Cretaceous and finally collided with Borneo mainland [5-7].

Central Luconia is subdivided into numbers of regional lows and highs that are partitioned into localised extensional horsts and grabens trending systematically in SSW-NNE and WSW-ENE compressional structures [8]. The structural highs are hosting the Middle to Upper Miocene carbonate reservoirs. However, the geometry, shape and orientations of the carbonate build-ups are not consistent throughout the province [9] (Figure 2). In the southern part, majority of the carbonate build-ups are oriented in NNE-SSW and turning to NE-SW at the transition from the southern region to the central region. The orientation of platforms in the central part is mostly in E-W direction, while the platforms in the northern part are oriented in NW-SE, with a few in NE-SW directions. The inconsistency in the limestone build-ups orientation is pre-evaluated to reflect the basement topography and structure underneath the sedimentary deposition. However, this remains inconclusive as a result of limited high-resolution data.

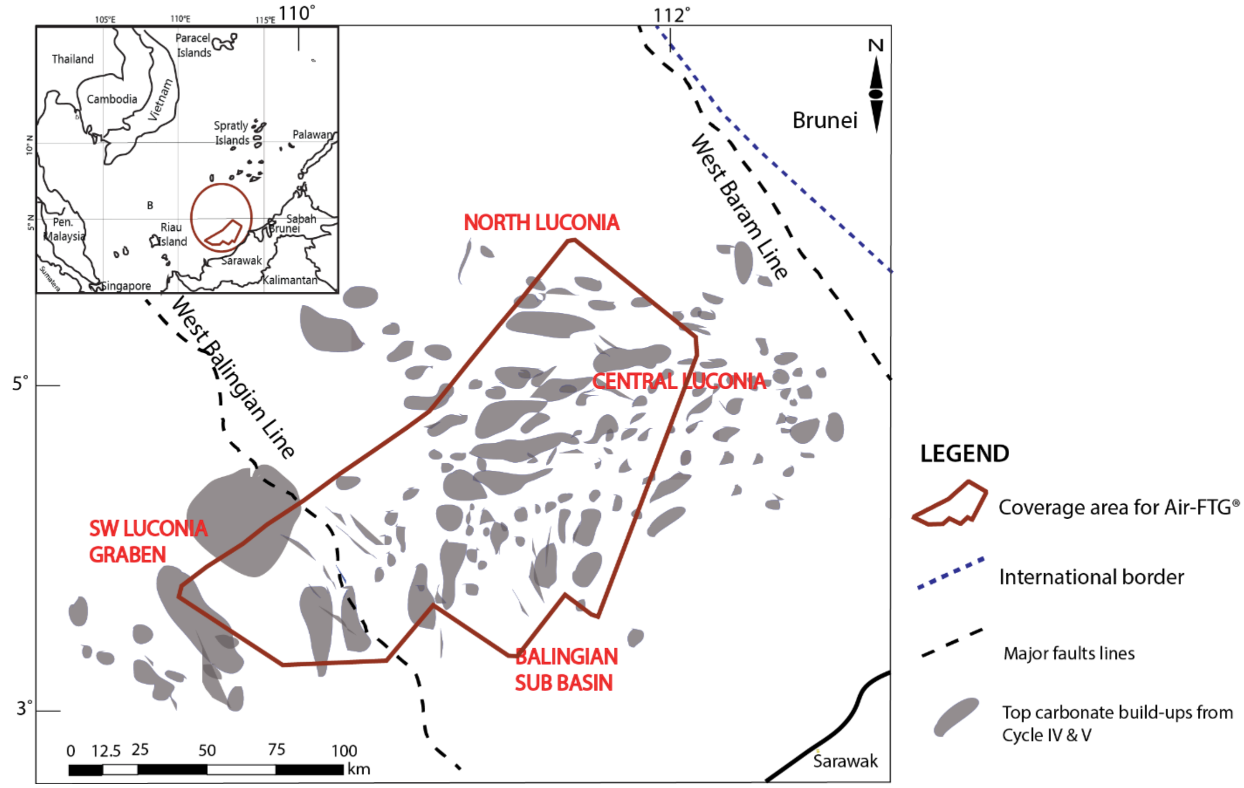

Figure 1. The location of airborne gravity survey in Central Luconia Province in offshore Sarawak, Malaysia. Central Luconia is bounded by other geological provinces in offshore Sarawak such as North Luconia, SW Luconia and Balingian sub-basin

3. Material and methodology

This study utilized the depth (Z) domain from the airborne gravity data acquired by Bell Geospace Limited (BGL) in 2014 which include the long wavelength and short wavelength data from Tz, Tzz, Txz, Tyz and Contact Lineament Processed (CLP) from three difference wavelengths. The raw airborne gravity data was acquired through GGI equipment that was mounted on Basler turbo BT-67 aircraft (C-FTGI). The survey was recorded with geographical co-ordinates in the WGS84 datum and Universal Transverse Mercator (UTM) projection zone 49N [10].

The gravity data was processed through High-Rate Post Mission compensation, line correction and levelling, followed by noise reduction and Contact Lineament Processing (CLP). CLP is a method that applies directional filter in processing the full-tensor Gradiometry data and it helps in assessing the relationship between different representations of an invariant tensor field from the measured gravity tensor (Tz).

In this work, the data are sorted into short and long wavelengths. Short wavelengths data focused on structures and geometries of the basin at shallower depth while long wavelengths data are utilized for the interpretation of deeper subsurface structures. Short wavelengths data include Tzz and CLP data for 5-20 km wavelengths. While, long wavelengths data include Tz and CLP data for 50-100 km wavelength. Intermediate wavelengths data are incorporated in this study to facilitate the subsurface zone between the shallow and deep sections. The intermediate wavelengths data are from Txz and Tyz components as well as CLP data of 20-50 km wavelength. Table 1 summarized the data utilization for different wavelengths and subsurface depth.

Table 1. List of datasets utilized for this study and their purposes

Data type	Unit	Short/Long wavelengths	Purpose	Short form
Computed Free Air Gravity for low frequency	mGal	Long	Geometry & Structure of the basin (deeper section), density variations	Tz
Computed Free Air Gravity for high frequency	mGal	Short	Geometry & Structure of the basin (shallow section), density variations	Tzz
Computer Free Air Gravity for horizontal direction (x)	mGal	Intermediate	Structure of the basin at intermediate depth	Txz
Computer Free Air Gravity for vertical direction (y)	mGal	Intermediate	Structure of the basin at intermediate depth	Tyz
Contact Lineament Processed Data (5-20 km)	Eotvos/m	Very Short	Structures at very shallow depth	CLP_short
Contact Lineament Processed Data (20 -50 km)	Eotvos/m	Intermediate	Structures at intermediate depth	CLP_int
Contact Lineament Processed Data (50-110 km)	Eotvos/m	Long	Structures at deeper depth	CLP_long

The airborne gravity data are filtered with continuity and apparent susceptibility filters before generating the gravity anomalies maps. The gravity anomalies maps are then generated through kriging technique and smoothed to reduce the irregularities and craggy look on the map. Changes in the gravity response as seen on gravity anomalies maps reflects changes on the densities of the lithology and geological bodies in the subsurface. Any drastic changes are marked with straight to curvy lines, following the shapes of the geological bodies presented on the anomaly maps. The interpreted lineaments are assumed to represent the structural trends in the subsurface of Central Luconia at different depth ranges, depending on the wavelengths of the data. The strikes for the structural trends are measured using semi-circular protractor. All measured strikes directions are plotted on the rose diagrams [11] for comparison and evaluations.

4. Results

4.1. Short wavelength airborne gravity

Structural trends on Tzz gravity anomaly map yield NW-SE to NNW-SSE (Figure 3a) structural trends. The highest gravity anomaly observed on Tzz gravity anomaly map is found in the south west of the survey area with gravity values of 15 to 20 MGal. The lowest negative gravity anomaly is in the central section of the survey area with -5 to -10 MGal.

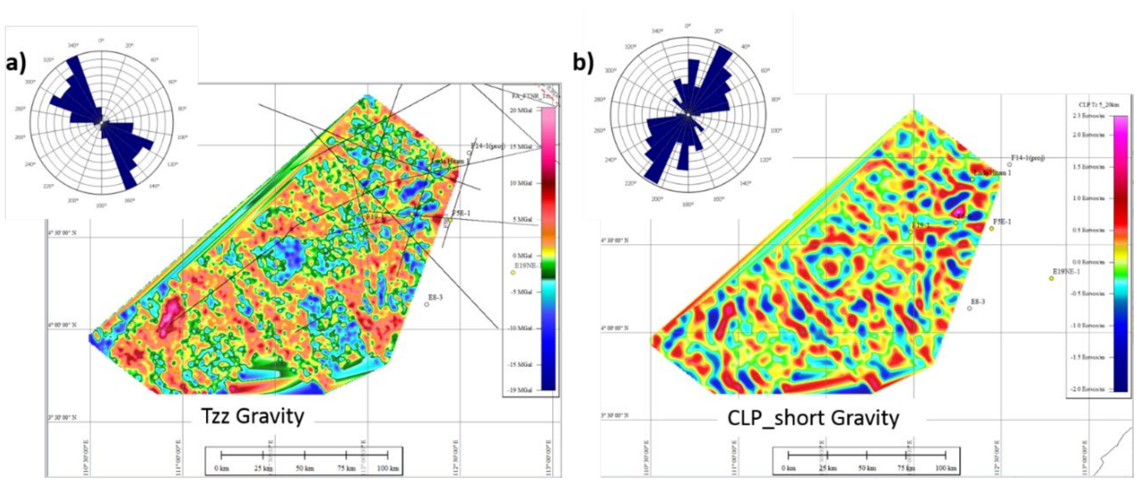

Figure 2. Gravity anomalies maps for short wavelength, reflecting shallower subsurface of Central Luconia. a) Tzz gravity anomaly map showing NW-SE as the dominant trend. Highest gravity anomaly is detected in the southwest of the survey area while the lowest negative gravity anomaly is detected in the central section of the survey area (both pointed with red arrows). B) Gravity anomaly map from CLP short wavelength (5-20 km) showing chaotic-elongated wormy texture with major structural trend oriented in NE-SW direction

Contact Lineament Processed (CLP) for short wavelength (5-20 km) possess major NE-SW structural trends with nearly N-S auxiliary direction (Figure 3b). Apart from that, other directions in NW-SE and NNW-SSE are observed too. All the interpreted structural trends on CLP_short data gives wormy- chaotic texture, indicative for multiple orientations in lineaments at the shallower subsurface. The short wavelength data is assumed to represent the subsurface at depth 2.5 to 10.0 km, and this include majority of the sediments from Cycle III to VIII that were deposited in Central Luconia Province, including the Miocene carbonate build-ups in Cycle IV and V.

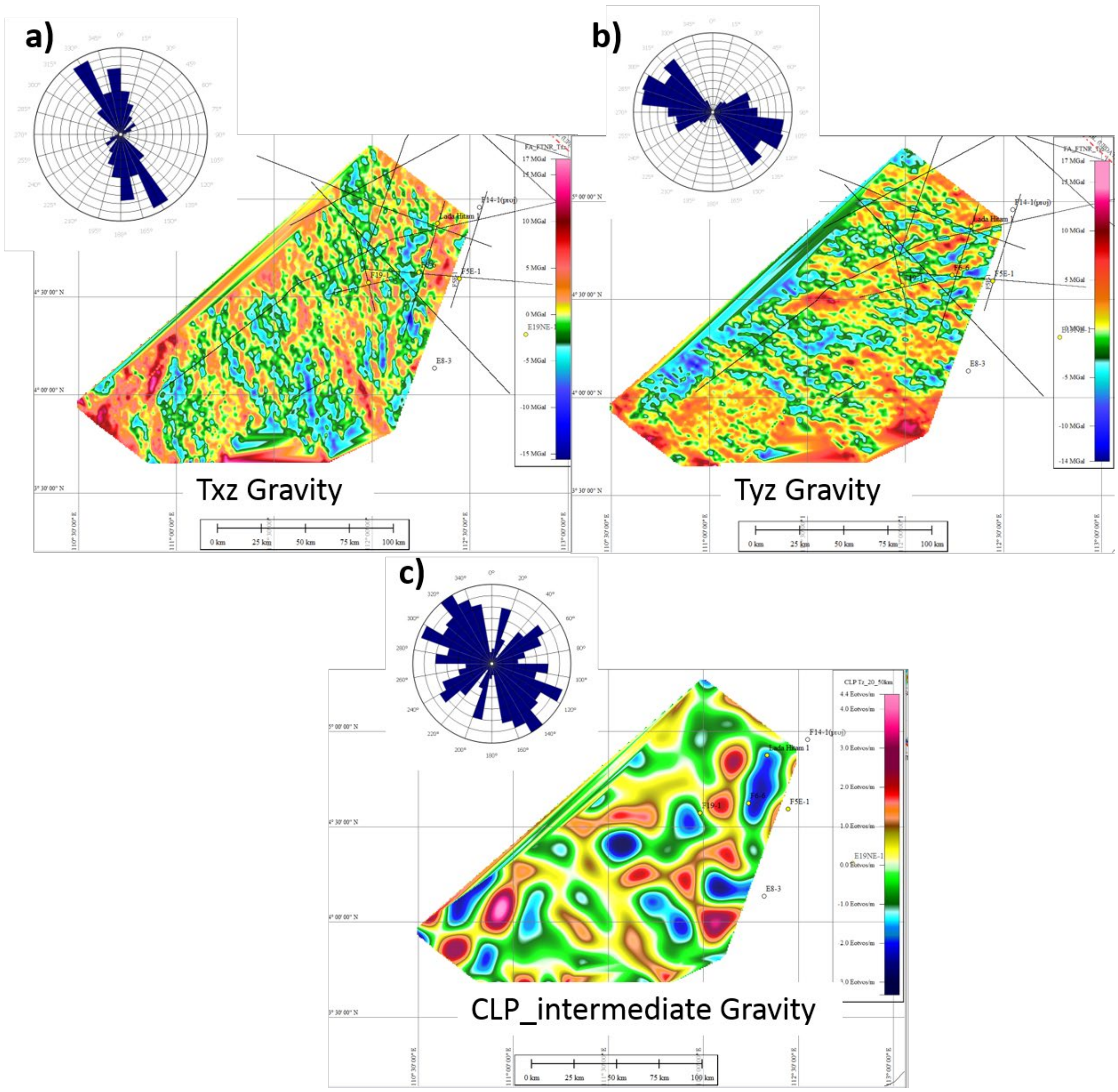

Figure 3. The intermediate wavelength (intermediate depth) gravity anomalies maps. A) Txz gravity anomaly map representing NNW-SSE to N-S structural orientation. B) Tyz gravity anomaly map showing NW-SE to E-W structural orientations. C) Contact Lineament Processed of intermediate (20-50 km) wavelength reflecting structural trends in almost all directions, with NW-SE orientation stands out

4.2. Intermediate wavelength airborne gravity

The intermediate wavelength airborne gravity data represent subsurface that is moderate, not too shallow and not to deep. It provides link in between the short and long wavelengths gravity anomalies interpretation. Txz, Tyz and CLP_inter with 20-50 km wavelength are classified for intermediate wavelength data (Table 1). The intermediate wavelength data is assumed to represent the subsurface at depth from 10 to 25 km. At this depth, the older sediments Cycle I and II might be preserved, as well as the Pre-Cycle layers.

Txz gravity anomaly map represents depth domain of the X-tensor (horizontal). The structural analysis on the map possesses NNW-SSE to N-S dominant orientation with minor NE-SW trend (Figure 4a). Meanwhile, the Tyz gravity anomaly map that represents the depth domain of the Y-tensor (vertical) is reflecting NW-SE to E-W dominant trend and minor NE-SW (Figure 4b). Contact Lineament Processed (CLP) data for intermediate wavelength gives structural trends in almost all directions. Majority of the lineaments on CLP_intermediate wavelength is oriented in NW-SE with some in NE-SW, but all other directions are presence too (Figure 4c). This has to be treated with cautious because the measurement of the strike orientation on CLP_intermediate wavelength data might include the left-over artefacts from the processing of the data.

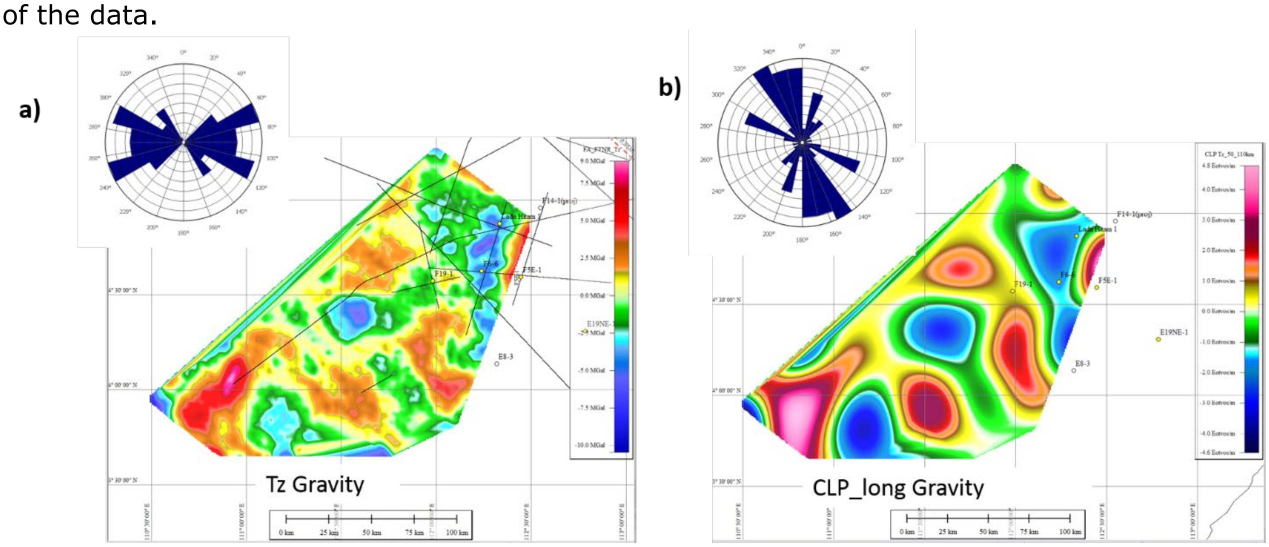

Figure 4. The long wavelength gravity (deep subsurface) anomaly maps. a) Tz gravity anomaly map represents structural trend in NW-SE and NE-SW with hint of E-W direction. B) Contact Lineament Processed (CLP) long wavelength (50-110 km) gravity anomaly map showing dominant NW-SE orientation with minor NE-SW

4.3. Gravity response surrounding Miocene carbonate build-ups

Top carbonate map as presented in [8] is overlaid with Tzz gravity [Figure 6] anomaly map since this map represent sediments deposited within shallow subsurface (possibly within 2.5 to 10.0 km depth). A comparison of Tzz map and distribution of the top carbonate build-ups is conducted to find the relationship of airborne gravity response with the growth of carbonate build-ups in Central Luconia.

From the observation, Miocene carbonate build-ups in Central Luconia tend to grow on either low gravity response, that been surrounded by positive gravity anomalies. Meanwhile, map of Figure 6 shows most carbonate build ups in West Luconia developed on highest positive gravity response. Generally, the subsurface of West Luconia is covered with high gravity anomaly, while the subsurface of Central Luconia is dominated with low and high gravity anomalies, where carbonate small-scale carbonate build-ups developed, as compared to big-size carbonate build-ups in the West Luconia Province. The reflection on the size and gravity response for the carbonate build-ups in Central and West Luconia is indicative for intense structural forces within Central Luconia had created variations in the topography (low and high relief) of the subsurface of Central Luconia. Meanwhile, in West Luconia, the carbonate build-ups are growing on high-relief structures, which might represent uplifted basement topography in West Luconia.

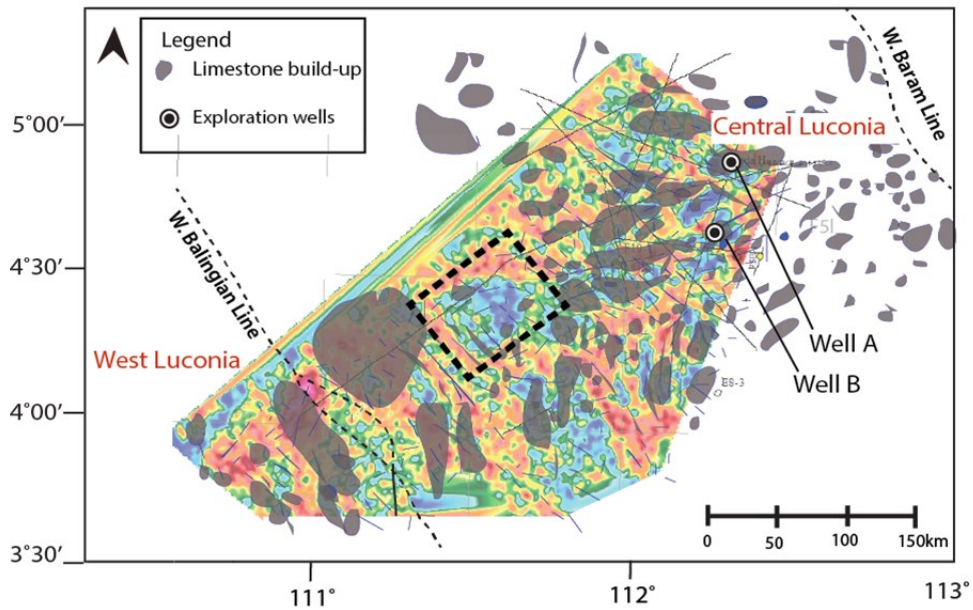

Figure 6. The top carbonate adopted from [8] is overlay with Tzz gravity anomaly map to show the relation of Miocene carbonate build ups with the gravity response. Dash rectangle box is highlighting the circular structure discussed in the text

An obvious circular structure (rectangle in Figure 5) is recognized on the gravity anomaly maps (Tzz and Tz of Figure 3a & 5a). This circular structure is dominated by negative gravity response (-5 to -10 mGal). Although the areas of low gravity anomalies are prominent area for Middle to Upper Miocene limestone (Cycle IV & V) reservoirs which is commonly located in elevated topography, the circular structure seen on the airborne gravity maps does not intercept with Middle to Upper Miocene top carbonate. Commonly, negative gravity anomaly with low density show possibility of depressional structure at depth [12].

It is suspected that the circular structure represents depression of the basin, within older sediments of Cycle I-III. This is related to high porosity Cycle II or III build-ups that have been interpreted by [13-14]. Cross examination with the sonic and density logs for for two exploration wells nearby the circular structure reveals average porosity of 20-22% in Cycle IV and V carbonate and bulk density of 2.36 g/cm^3 in the formation. While Cycle III mixed clastic carbonate rocks in both wells yield 17-18% porosity with increase in bulk density to 2.5-2.7g/cm^3. The sediments in Cycle II from both wells are dominated by clay to mudstone with porosity 14-15% and bulk density ranging from 2.5-2.7 g/cm^3. Within Cycle II and III, the average porosity examined is more than 15% and this is considered as a good porosity for potential hydrocarbon reservoir. As such, this circular structure with low gravity anomaly is suggested for potential area for exploration.

5. Discussion

Comparison of structural trends from the depth (Z) components of the airborne gravity include short, intermediate and long wavelengths reveal changes in the orientation of the structural trends at different subsurface depth in Central Luconia Province. Although the exact depth is undetermined through airborne gravity data, the gravity anomalies maps processed at different wavelengths ranges allow estimation on the depth.

At very shallow depth, major structural trends for the faults and lineaments are mainly in NE-SW directions, with chaotic looking CLP_short anomaly map. The structural trends presented at this depth has possibility to be related with gravitational tectonics from the thick sedimentation in the offshore Sarawak [15-16]. As depth increase, the structural trend is dominated in NW-SE directions. This is observed on Tzz and Txz gravity anomalies maps. Meanwhile, the vertical component of the depth domain (Tyz) begins to express E-W orientation in the structural trend, while still preserving the NW-SE direction. NW-SE direction is still recorded at the deep subsurface of Central Luconia, as imaged on the CLP_long wavelength gravity anomaly map. Tz gravity anomaly map that represents the long wavelength for imaging deep subsurface layer preserved an E-W direction, along with NW-SE and NE-SW trends. The dominant NW-SE trend follows the direction of two major faults that bounded Central Luconia Province, which are the West Baram Line and West Balingian Line (Figure 2). Thus, majority of the faults in Central Luconia formed at the same time or after the formation of these two major fault lines. The movement of West Baram and West Balingian Lines directly impacted the sediments in Central Luconia, creating internal faulting in the same directions. Meanwhile, the E-W trend only appears in the deep subsurface of Central Luconia and has possibility to be related to the orientation of the magnetic basement of this area [17].

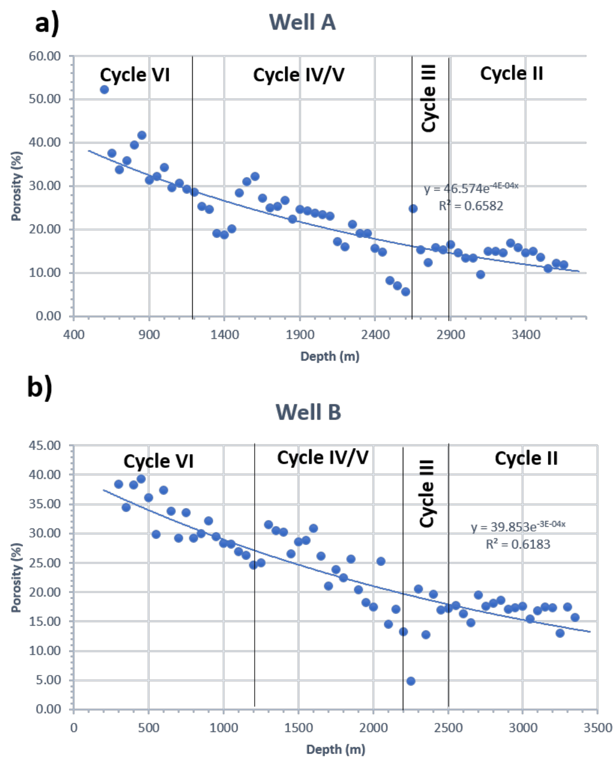

Figure 5. The porosity- depth cross plot for a) Well A and b) Well B. Both wells show general trend of decrease in porosity as depth increase with consistently moderate-good porosity at about 14-15% in older Cycle II and III sediment

6. Conclusions

Airborne gravity provides varieties of tensors from the depth (Z) domain to be analysed and this include Tz, Tzz, Txz, Tyz and Contact Lineament Processed (CLP) data at variable wavelengths. The interpretation of lineaments on these different gravity anomalies map provide main structural trends at different subsurface depth to be recorded and mapped. Overall, high resolution airborne gravity data helps to differentiate main structural trends in the subsurface of Luconia, and this could be done due to variations in the sedimentation from clastic to carbonate depositions within Central Luconia. This study concludes:

- NW-SE trend is dominant in all subsurface depth of Central Luconia and it represents impact from the West Baram and West Balingian Lines that bounded Central Luconia in the east and west.

- E-W structural trend only appears in the deep subsurface on long wavelength data and Tyz gravity data. It is interpreted to be related to the orientation of basement in Central Luconia. Further evaluation on magnetic data is recommended for confirmation.
- Airborne gravity analysis in Central Luconia provides good quality and high-resolution data due to variations in the sedimentation of clastics and carbonate rocks.
- Miocene carbonate build-ups in Central Luconia are drilled on mostly low gravity areas and exhibit small-scale build ups as compared to build-ups in West Luconia which grows bigger and mainly found on the high gravity response areas.
- A circular structure with depressional features and dominated by low gravity anomaly in the central section of the study area is suggested for potential hydrocarbon exploration.

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