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Subsurface Structure Identification from Gravity Modelling of Silangkitang Geothermal Field for Future Injection Well Targeting

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ABSTRACT

The injection well has been frequently overlooked by the geothermal developer if compared to production wells. Moreover, the sustainability of reservoir geothermal is determined by the right location of injection wells to provide reservoir pressure support and avoid cooler marginal fluid to enter the reservoir. The robust well targeting of injection wells to hit the major subsurface structures that have a good connection to the reservoir are very important for the reservoir surveillance, one of the geophysical method to determine the major subsurface structures is a gravity modeling. The objective of this study is to provide geophysics point of view based on a gravity modeling to characterize the faults/structures distribution in Silangkitang in order to identify future make-up well drilling target. A total of 116 gravity stations measured at Silangkitang has passed standard correction such as tide, sensor height, and drift corrections. The spatial corrections such as latitude correction, Free-air correction, Bouguer correction, and Terrain correction were conducted to obtain the Complete Bouguer Anomaly (CBA). The CBA have been filtered to separate the regional and residual anomalies, which associate with deep and shallow anomalies respectively. The result of the CBA, regional anomaly and residual anomaly model enhance the interpretation of the major trend of NW-SE of both Barumun (east) and Angkola (west) faults as identified by the surface geological map. The Forward modeling was also performed to construct the subsurface model of the gravity data. The forward modeling could model the presence of basement rock in the east and west associates with high anomaly while the volcanic-sedimentary product in the center of graben associated with lower gravity response. First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) from the study also strengthening the kinematic analysis of both Angkola and Barumun faults which associated with normal fault, as indicated by geological study as dextral strike-slip (normal fault with shear component). In conclusion, the study has shown that the gravity study could help to analyst the geological concept in Silangkitang, particularly delineating the extent of major faults/structures and lithological boundary which is very useful to assist the well targeting of future make-up well drilling in Silangkitang.

1. INTRODUCTION

The Silangkitang (SIL) field is a part of Sarulla Geothermal Field which located about 30-km northwest of the town of Sipirok within the Sarulla graben. The reservoir characteristic of Silangkitang is a liquid dominated system with temperature higher than 280°C and relatively moderate gas <1 wt% in reservoir liquid (Simatupang, 2020). The prospect was initially identified by two sets of thermal features: a series of fumaroles on the eastern edge of the valley aligned along a 1.75 km segment of the Great Sumatra Fault, and numerous boiling chloride springs located within the valley in the same vicinity. Further exploration work identified several other characteristics of the prospect that made it even more attractive. These include: a young (120,000 year old) rhyolite lava dome at the southeastern end of the prospect, more boiling hot springs on the western side of the valley, and an area of low resistivity associated with the eastern springs and fumaroles that was identified by geophysical surveys (Hickman et al., 2004). The first systematic exploration study conducted in 1980s by PERTAMINA ranked Silangkitang as one of the attractive projects in Sumatera (Ganefianto et al, 2015). In early 1990s, the extensive exploration program include exploration drilling was continued by Unocal which resulted the reserve confirmation of 80 MWe for 30 years at Silangkitang (Gunderson et al, 2000). In 2017, Sarulla Operation Limited (SOL) has successfully installed 110 MWe capacity in Silangkitang by applying technology optimization of Integrated Geothermal Combined Cycle (IGCCU).

Silangkitang tectonic setting in Sarulla Graben is associated with major right-lateral, strike-slip fault system (Hickman et al., 2004; Gunderson et al, 2000; Satya et al, 2018) which of GSFZ. The GSFZ extend 1650 km long from Aceh to Lampung, the dominating NW-SE faults creates secondary fault structures N-S (extensional fractures), NNE-SSW (synthetic Riedel shears), and NE-SW (antithetic Riedel shears). At Silangkitang the NW-SE orientation act as main permeable zone (Nukman, 2014) which been controlled by the extension of Sarulla Graben perpendicular to GSFZ. SIL lies above a local sub-graben formed between the Tor Sibohi fault and the intersecting Hutajulu fault overlaid by Neogene, Quaternary volcanic and volcanoclastic rocks cap Tertiary sediments (Hickman et al., 2004; Satya et al, 2018). In the east, The Paleozoic Meta-sediments are exposed at the surface east of the GSFZ as the eastern boundary of Silangkitang reservoir.

Satya (2018) has emphasized that the production and injection wells that penetrated GSFZ only obtained good permeability toward the east, which according to detailed mapping shows the main releasing bends and fault steps occur along the Eastern GSFZ within Sarulla Graben. It is likely that the main permeable zone at SIL mainly controlled by fault and fractures of eastern GSFZ or knowing as fault controlled system, the implication of this structural controlled will limit the natural convection and the reservoir is constraint into structural damage zones as explained by Wallis (2017).

After two (2) years of operation, Simatupang (2020) has acknowledged the chemical response in the production area that indicates an injection breakthrough from injectate liquid without significant enthalpy impact. Most of production and injection wells are drilled perpendicular toward single eastern Great Sumatra Fault Zone GSFZ, while some injection wells drilled away from eastern GSFZ but do not provide adequate injection capacity (**Figure 4b**). A reservoir optimization study has been conducted to shift the injection wells location further northwest or southeast of the production area, such as geological mapping, geochemistry tracer and reservoir

simulation to characterize the main fault/structure which have a good connection for providing pressure support but has sufficient distance to avoid rapid cooling to the reservoir. The importance of this fault/structure characteristic in Silangkitang needs to study further detail using subsurface tools such as gravity method to enhance the understanding of the subsurface faults/structures of Silangkitang for future well targeting of make-up injection wells. The gravity method is selected since it has good lateral sensitivity and could map the density contrast between low and high-density rocks, perhaps this correlation could identify the eastern boundary of Silangkitang reservoir where the Paleozoic rock outcropping to the surface. This situation juxtaposing the basement rock of different densities in the East compared to the Graben fill product such as volcano-sedimentary rock in the Western area.

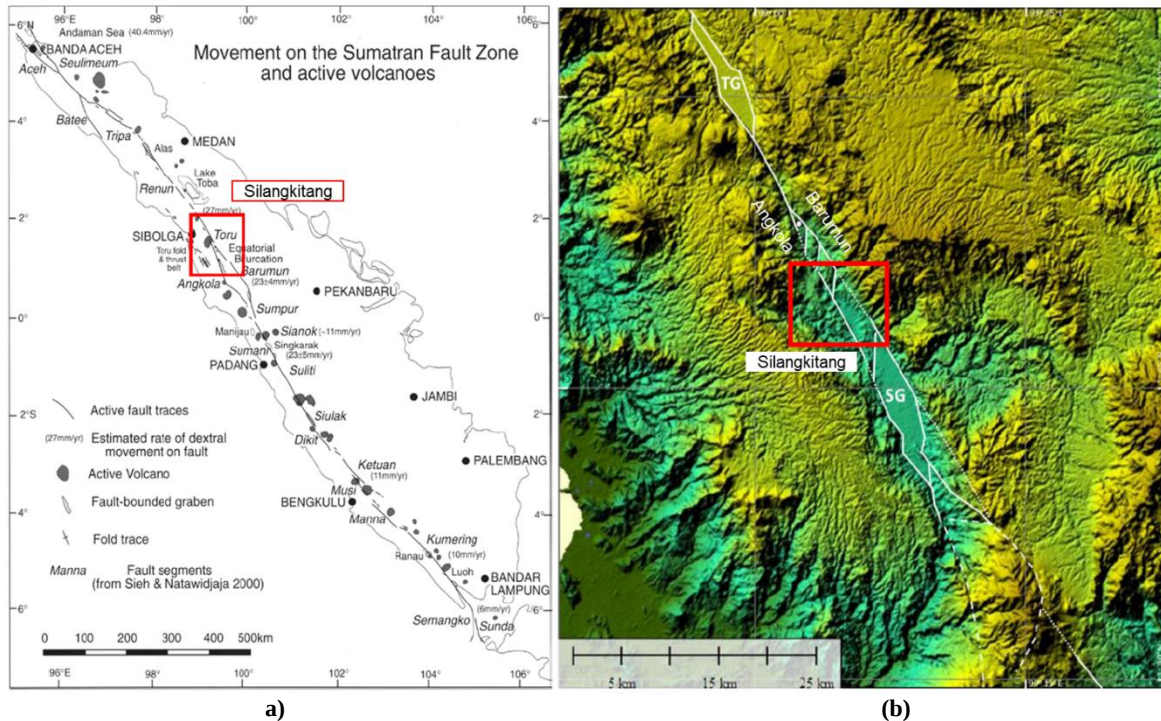


Figure 1: (a) Active traces of the Sumatran Fault System identified by their geomorphic expression, fault segments and estimated rates of dextral movement, the location of active volcanoes, lakes and extensional graben (Sieh and Natawidjaja, 2000). (b) Two (2) main Graben Tarutung (TG) in the Northwest and Sarulla (SG) in the Southeast which created from two major segment Barumun and Angkola fault segments.

2. TECTONIC AND GEOLOGICAL SETTING

The SIL geothermal field developed in the northern end of Sarulla Graben is bounded to the east by Barumun Fault and to the west by Angkola Fault (**Figure 1**). It is in SIL area where the Barumun Fault and Angkola Fault started to diverge, creating a region of tensional stress at its tip, forming the Sarulla Graben. Therefore, the Sarulla Graben probably not a typical pull-apart basin formed by slip interaction of two overlapping fault segment (SOL-UGM, 2020). The Barumun Fault is the most active and the largest throw, as indicated by striking fault escarpment and half-graben geometry in seismic profiles. Hickman et al. (2004) later applied different named for Barumun Fault as the eastern bounded fault, i.e. Hutajulu Fault for northern segment and Tor Sibohi Fault for southern segment.

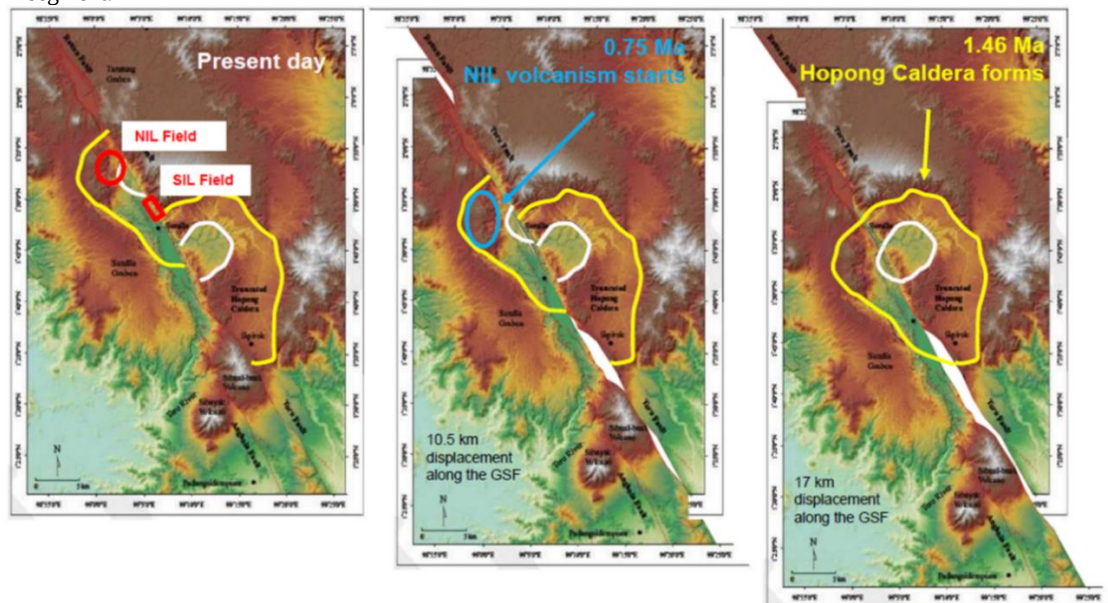


Figure 2: The origin of Toru undifferentiated volcanics that overlay Sarulla Graben (SG) from Hopong Caldera (modified from Hickman, 2004)

The oldest rock of unit of SIL is a Metamorphic Rock associated with Paleozoic Age outcropping in the eastern side of GSFZ (Moore et al., 2001). In the west, a relatively younger unit presence in the western side of GSFZ as Simardangiang Pyroclastic Breccia Unit, the volcanism of Simardangiang is presence at Miocene age according to the geology study in NIL (SOL-UGM, 2020). In the middle of Sarulla Graben (SG), the younger of volcanism deposited in SIL is Hopong Volcanic Unit originated from southeast of SIL area (**Figure 2**). This volcanism was active during the Pleistocene epoch with 9 km diameter of eroded caldera massively truncated by the GSFZ, forming the eastern wall of Sarulla Graben (Hickman *et al.*, 2004). The younger volcanic product of Lapilli Tuff and Clay Tuff Unit filled the Sarulla graben from Northwest to Southeast part of Silangkitang. The latest volcanism deposited in Sarulla Graben is Toba tuff unit, the unconformity is expected in the west due to Toba tuff unit deposited above the Simardangiang Pyroclastic Breccia later followed by alluvium product. The outcrop of oldest rock in the east and west of Silangkitang revealed the tectonic setting of Sarulla Graben (**Figure 3**).

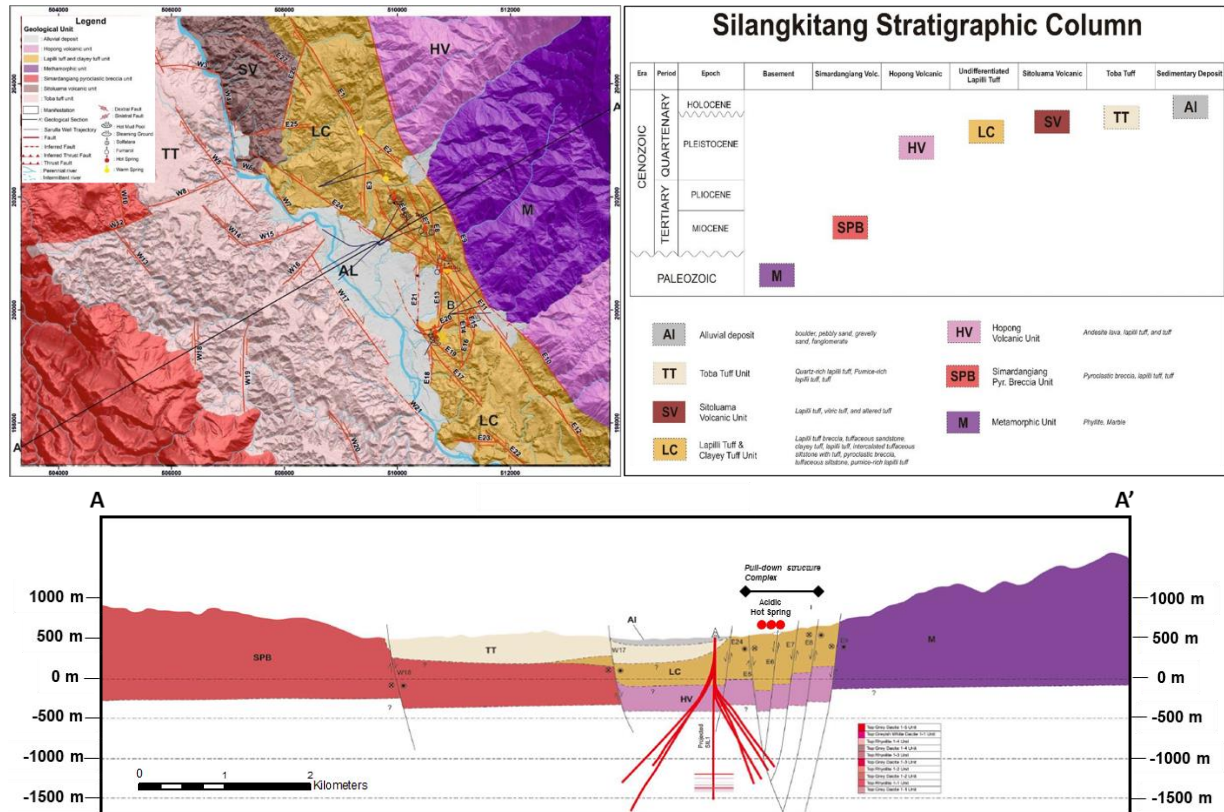


Figure 3: Geological model of Silangkitang

3. GRAVITY DATA (COMPLETE BOUGUER ANOMALY - CBA)

Gravity survey is a standard best practice of geophysical method to identify the variation of subsurface rock densities for a resource delineation particularly in Sumatra in which the geothermal system dominantly controlled by GSFZ. In Sumatra, most of the preliminary structure mapping for geothermal exploration has been conducted using either open-access satellite gravity data such as Topex or detail gravity survey in the early stage of exploration to reduce the permeability risk of Well Targeting. Unocal collected totally 116 gravity measurement stations at Silangkitang during the exploration in early 1990s the absolute gravity data as the output. The absolute gravity data has been processed with standard correction such as tide, sensor height and drift corrections thus the further correction required is the spatial correction. The spatial correction such as latitude correction, Free-air correction, Bouguer correction and Terrain correction was conducted to obtain the Complete Bouguer Anomaly (CBA), specifically the reduction density of 2.6 g/cc is applied from Parasnis method to calculate the Bouguer correction, and the density calculation is suitable with the dominance of igneous rocks and metamorphic rock in the Silangkitang area. The gravity data was proceed and obtained a map of CBA as shown in **Figure 4(a)**. The CBA values in the study area varied from -41 mGal to -69 mGal with the high value relatively associated with basement rock in the east (Metamorphic unit) and west (Simardangiang Pyroclastic Breccia unit). On the other hand, the low-density value is located near the center of graben as volcano-sedimentary basin fill products (Hopong Volcanic unit, Lapili Tuff and Clayed unit, Toba Tuff unit, Sitoluama unit, and Alluvial Deposit). The result of CBA map also enhances the interpretation of the major trend of NW-SE of both Barumun (east) and Angkola (west) faults along Great Sumatra Fault Zone (GSFZ) as identified by the surface geological map.

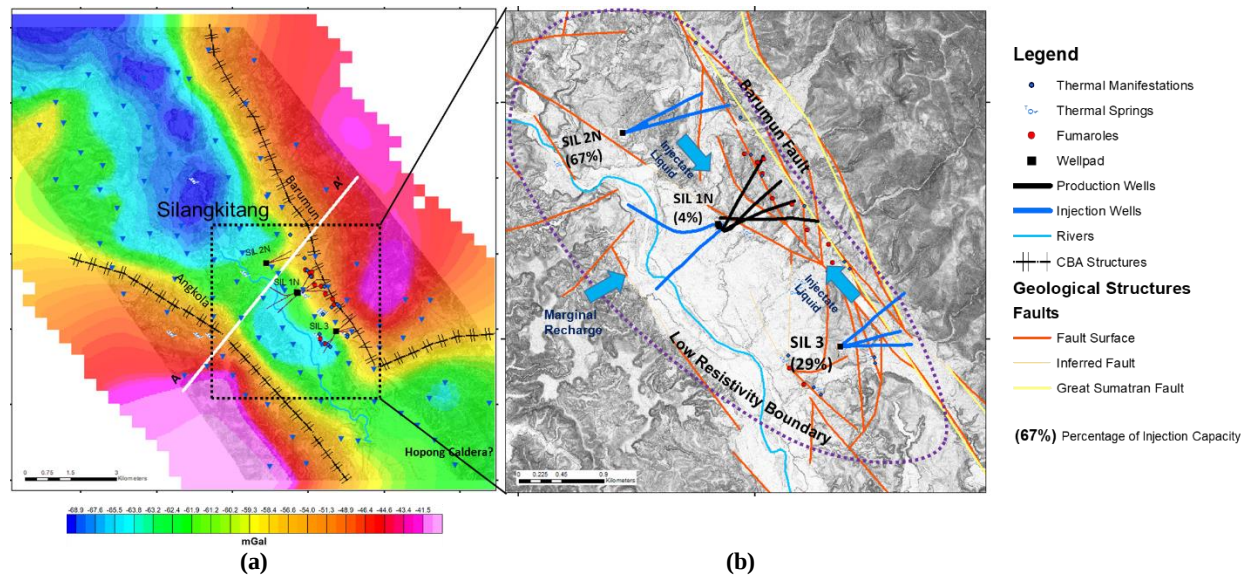


Figure 4. (a) The major structural trends from Complete Bouguer Anomaly (CBA) indicates two high-density gradient of NW-SE trend associated with GSFZ. The low density in the southeast of SIL associated with the morphology of Hopong Caldera (cross section A-A' represent the 2D forward modeling line). (b) Map of SIL injectate liquid distribution, marginal recharge occur from west of Production area and injectate liquid return from northwest and southeast injection wells (modified from Simatupang, 2020).

4. GRAVITY MODELING

After the CBA map is processed from the two steps correction of temporal and spatial, filtering methods were assigned to eliminate the strong regional trend particularly affected by GSFZ. The high-density contrast is produced from the lithology contact between volcano-sedimentary graben fill products with the outcrop of metamorphic unit and pyroclastic breccia unit in the east and west. The result of filtering regional and residual are presented in **Figure 5**.

Complete Bouguer Anomaly (CBA) data is filtered using the Butterworth filter to separate the regional and residual (shallow) density contrast at certain depth. The residual anomaly is associated with high frequency meanwhile the regional anomaly is associated with low frequency. a Butterworth band-pass filter in a wavenumber domain with the low cut-off about 0.2 rad/km and high cut-off of 0.8 rad/km has been applied to obtain the residual gravity anomaly. Based on the analysis of the power spectrum response, the regional gravity responses the deep Paleozoic and tertiary basement in the Western and Eastern side with depth > 2 km. the residual anomaly map is derived by removing the regional anomaly from the CBA and shows the gravity response density contrast of depth < 2km. Overall the regional and residual shows major trend of NW-SE trend on east and west of SIL, but the residual anomaly map shows the high density anomaly in the northwest probably associated with Namora-I-Langit (NIL) Volcanic complex. This high anomaly gravity of the residual is likely to be caused by volcanic/magmatic bodies rather than deep Paleozoic basement structures since the gravity response of volcanic/magmatic bodies in this location is relatively radial rather than elongating along GSFZ from residual anomaly.

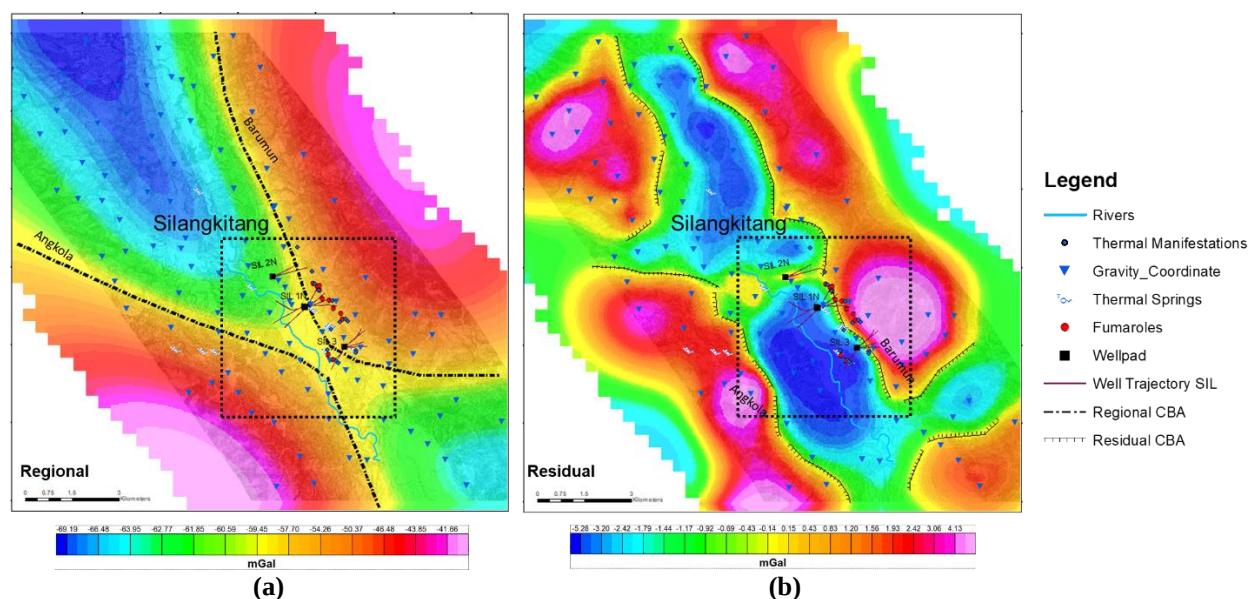


Figure 5. (a) Regional anomaly which shows density contrast at depth > 2 km with major trend NW-SE (b) Residual Anomaly reveals NW-SE major trend elongating along GSFZ in the middle of SIL field affected by shallow Paleozoic and Tertiary basement outcrop. High-density contrast in the northwest is probably associated with volcanic/magmatic bodies since the trend is relatively radial compared to the other trends.

Other methodology used to improve the fault/structure interpretation in Silangkitang are First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD). Rosid and Siregar (2017) has applied FHD to detect a shallow inhomogeneity (fault or lithology contact) contrast based on the horizontal changing of gravity value. While SVD method used to identify a type of fault (normal or reverse) based on the adjacent contrast of high and low anomaly, however shear fault could not be able to detect by using SVD method. The type of fault is defined as a normal fault if the value of $g''_{max} > g''_{min}$ and reverse fault if the $g''_{max} < g''_{min}$. **Figure 6** show the response of FHD and SVD, FHD shows a high-density contrast on both east and west most likely associated with a major structure of Barumun and Angkola faults as identified by CBA, Regional, and Residual anomaly. Based on SVD, the fault kinematic of Barumun and Angkola could be identified by creating a cross section B-B' to analyze g''_{max} and g''_{min} of fault block 1 and fault block 2 (**Figure 7**). Based on SVD analysis, Fault block 1 and 2 are associated with normal fault, this interpretation supports the fault kinematic of a GSFZ that is a normal fault with Strike-Slip component (Dextral Strike-Slip Fault).

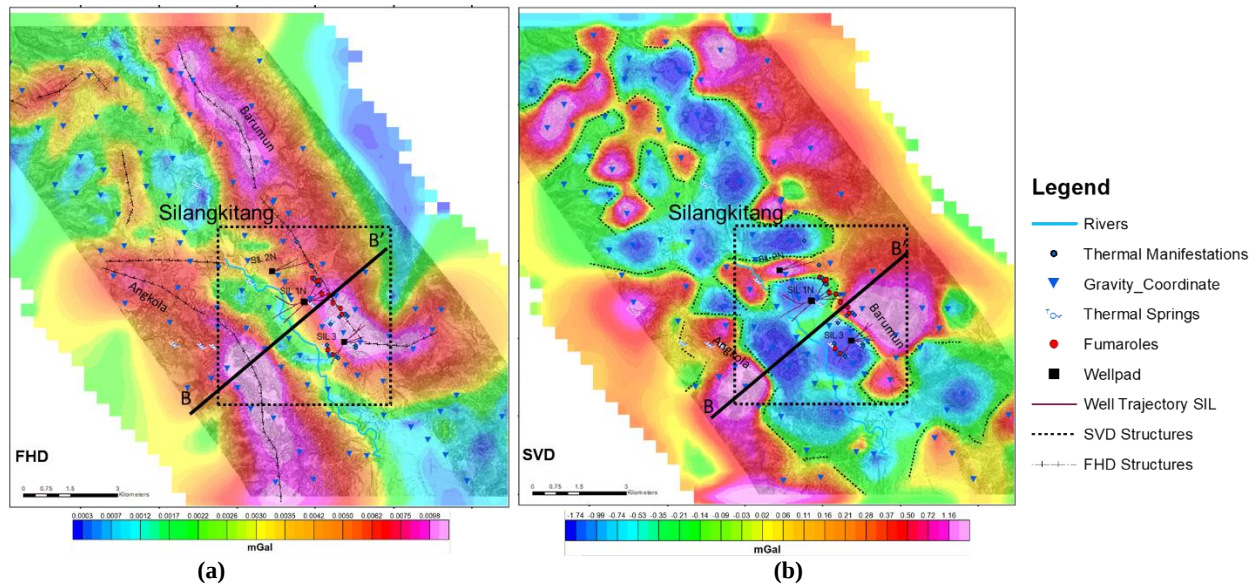


Figure 6. (a) Contour map of FHD shows two main high-density contrast on west and east associated with Barumun and Angkola faults. (b) Contour SVD map of Silangkitang.

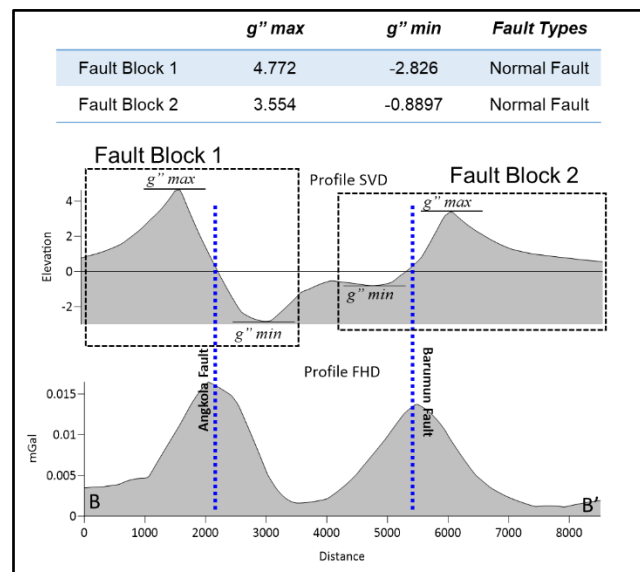


Figure 7. Cross section of line B-B' on SVD and FHD to identify the fault kinematic, both fault block 1 and 2 are associated with normal fault (see cross section line in Figure 6).

Forward modeling is performed to construct the subsurface model based on the gravity response. The forward modeling is assumed that the model layers (lithology unit) were homogeneous, constant density and relatively constant thickness. Initially, the model layers is assumed laterally extent to infinite distance although actually the good match could be obtained by extending the layers 50 km in both direction. To test the graben concept of GSFZ in SIL, one (1) profile is constructed to review the gravity and geology model (**Figure 8**). The objective of this cross section is to prove the consistency of geology concept in Silangkitang where it is associated with Sarulla Graben. The outcropping of Metamorphic rock in the east and Simardangiang Pyroclastic Breccia as tertiary basement rock in the west hint a high-density contrast in both direction. Cross section A-A' (see location on **Figure 4**) was located across high-low-high density contrast associated with high-density rock, adjacent with Angkola and Barumun Faults. The thickness of the lithological unit were based on the formation log of SIL fields as been modeled by Satya (2018) about geological model of Silangkitang. The Metamorphic unit applied as the 'basement rock' by adjusting its density to 2.8 g/cm^3 , following that the volcanic-sedimentary product such as Hopong Volcanic, Lapilli tuff and Clayed tuff, Toba tuff and Alluvial unit is assigned in the center associated with lower density value to match the observed model (**Figure 8**). As explained by McDonald and Gosnold (2014), it should be understood that the modeling of gravity (potential field data) is a non-unique process in that a number of

different models could generate similar gravity response. The author has elaborated the geological conceptual model from surface and wells to duplicate a tectonic setting of Silangkitang.

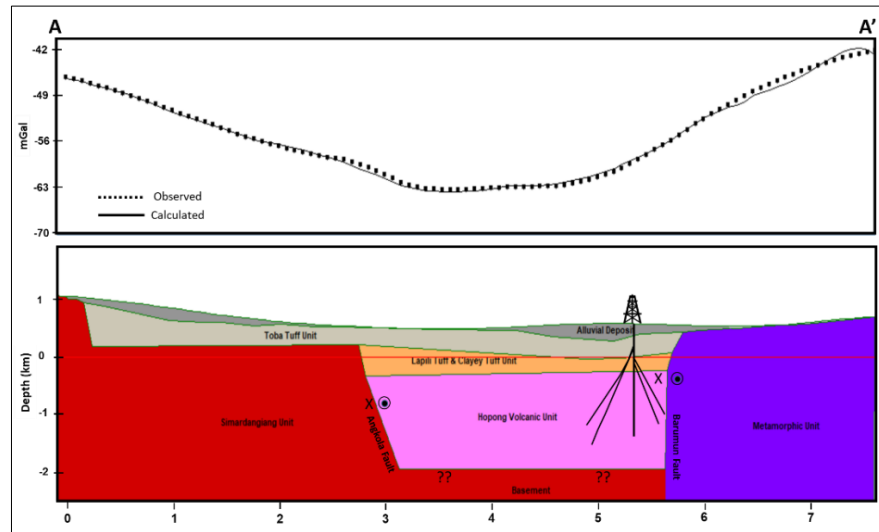


Figure 8. Model profiles and calculated gravity response versus observed values profile A-A' model unfiltered data from Complete Bouguer Anomaly (CBA). Cross section profile in figure 4.

5. CONCLUSIONS

The study has shown that the CBA, Regional and Residual gravity anomaly can be used to guide the geological concept of Silangkitang, particularly assisting the interpretation of major structure and lithological unit of a geothermal system in Great Sumatra Fault Zone (GSFZ). The gravity model suggests that the gross geologic structure of SIL is consistent as a typical fault-controlled system geothermal system (Satya, 2020). The near vertical faults associated with Barumun block constraint the distribution of geothermal system along the eastern GSFZ, perhaps eastern fault zone has a better connection to a deep magmatic plumed which feeds the high temperature fluid in Silangkitang. This configuration appears to be controlled by a half graben forming which create fault stepping with relatively lower dip angles fault in the west associated with younger lithological unit compare to metamorphic unit in the eastern side. Barumun and Angkola Faults act also as barrier and structural trap that have been proved by the wells drilling in Silangkitang.

Other methodology such as FHD and SVD could further enhance to interpret the shallow horizontal contrast of major faults and determine the fault kinematics that unsurprisingly support the fault kinematic of GSFZ as a normal fault with strike slip components. Since GSFZ is a major fault that extends from shallow to deep anomaly, thus it could be detected in various methodology from CBA, Regional, Residual, FHD, and SVD. Gravity Forward modeling could also perform in constructing Sarulla Graben where the basement rock outcropping in both west and east area and volcanic-sedimentary product in the center associated with lower density value. Again, it should be noted that the gravity (potential field data) is a non-unique process in that a number of different model could generate similar gravity response to duplicate tectonic setting of Silangkitang. However, the gravity forward modeling has replicated the Sarulla Graben setting to support the geological concept of Silangkitang Geothermal Field.

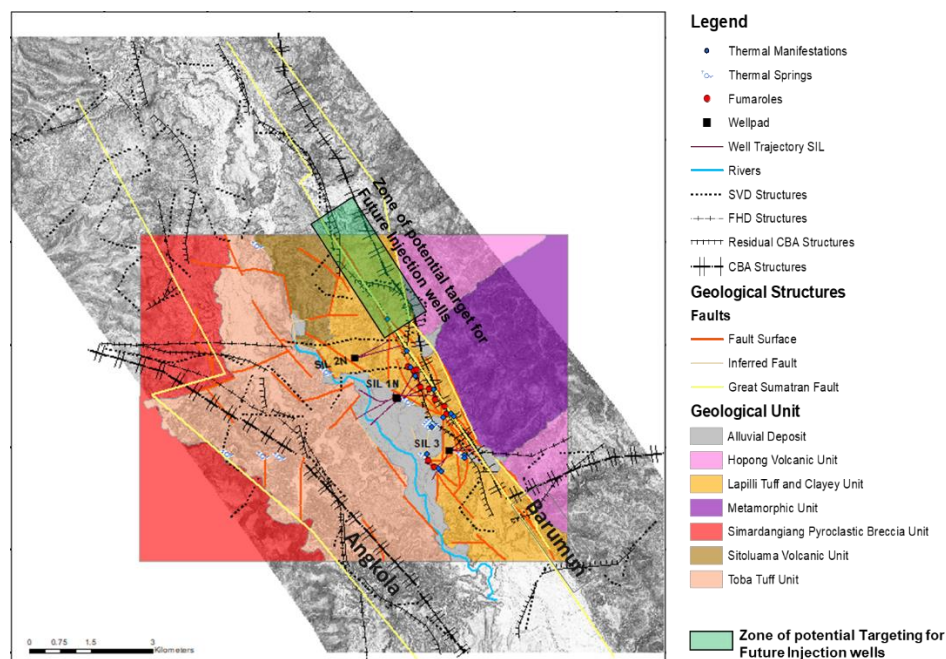


Figure 9. Map integration of all gravity anomaly of CBA, residual, SVD and FHD to determine the extent of Barumun Fault as favorable target of future SIL injection Wells

The results of the gravity modeling of CBA, residual, SVD and FHD has coherently revealed the extent of Barumun fault to northwest of Silangkitang (**Figure 9**). However, the extent of Barumun Fault to the southeast should be interpreted cautiously since it perhaps associate with low gravity anomaly of Hopong Caldera, the trend of high gravity anomaly contrast shifter to the east of GSFZ creates local low gravity anomaly in the southeast of Silangkitang. Based on the continuation of high contrast gravity anomaly to the northwest that associates with Barumun fault, the future injection wells of Silangkitang should be targeting these locations. The geothermal system in Silangkitang is associated with a fault-hosted system in which the reservoir hosted by one single major fault, the connectivity of injection result significantly expected to support the reservoir pressure since commonly it has limited lateral size. The strong gravity anomaly lineament to the northwest support the potential connectivity reservoir recharge from northwest of Silangkitang along GSFZ for the target of future injection wells.

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