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ANALYSIS AND MODELLING OF SUBSURFACE STRUCTURES WITH 3D INVERSION OF GRAVITY DATA USING SIMPEG OPEN SOURCE FRAMEWORK

ANALISIS DAN PEMODELAN STRUKTUR BAWAH PERMUKAAN DENGAN INVERSI 3D DAAT GAYABERAT MENGGUNAKAN FRAMEWORK OPEN SOURCE SIMPEG

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ABSTRACT
The gravity method is a geophysical exploration method based on measuring differences in gravity values caused by variations in density laterally under the earth's surface. Mapping using the gravity method can be utilized to obtain a representation of subsurface geological conditions based on density variations. In this research, the inversion process of subsurface models in geothermal areas is carried out, especially in the case of enhanced geothermal system development. Processing of gravity data is done by utilizing Python-based programming language to grid data and interpolation with ordinary kriging and spline interpolation methods. The results of the data interpolation will be compared to obtaining the best model based on the distribution of measurement points that can be used in Utah FORGE data, USA. The 3D gravity inversion process is performed by utilizing the discretize library and SimPEG to provide an overview of the source of subsurface anomalies with gravity data. Modeling was performed using synthetic data as a test of the inversion process and Utah FORGE field CBA data. The inversion results will be interpreted by correlating geological data to validate the interpretation results.

ABSTRAK
Metode gayaberat merupakan metode eksplorasi geofisika yang didasari oleh pengukuran perbedaan nilai gravitasi yang disebabkan oleh variasi densitas secara lateral dibawah permukaan bumi. Pemetaan menggunakan metode gayaberat dapat dimanfaatkan untuk mendapatkan representasi kondisi geologi bawah permukaan berdasarkan variasi densitasnya. Pada penelitian ini dilakukan proses inversi model bawah permukaan pada daerah panas bumi khususnya pada kasus pengembangan enhanced geothermal system. Pengolahan data gravity dilakukan dengan memanfaatkan bahasa pemrograman berbasis Python untuk melakukan grid data dan interpolasi dengan metode ordinary kriging dan spline interpolation. Hasil dari interpolasi data tersebut akan dibandingkan untuk memperoleh model terbaik berdasarkan persebaran titik pengukuran yang dapat digunakan pada data

Utah FORGE, Amerika Serikat. Proses inversi 3D gravity dilakukan dengan memanfaatkan modul discretize dan SimPEG untuk memberikan gambaran mengenai sumber anomali bawah permukaan dengan data gravitasi. Pemodelan dilakukan dengan menggunakan data sintetik sebagai uji coba proses inversi serta data CBA lapangan Utah FORGE. Hasil inversi akan diinterpretasikan dengan melakukan korelasi terhadap data geologi untuk memvalidasi hasil interpretasi.

INTRODUCTION

The gravity method is a geophysical method used in the investigation of tectonic studies, mineral exploration, and in engineering and environmental problems. Mapping using the gravity method can be applied to obtain an overview of subsurface geological conditions based on density variations Therefore, this research requires other solutions and alternatives to determine the subsurface model in geothermal areas, especially in the case of enhanced geothermal system development. Estimation with gravity in the EGS area is expected to be used to obtain information about the subsurface response based on physical properties and anomaly contrast.

The gravity data inversion process is part of the quantitative interpretation stage because it can obtain a density model based on information on the gravity data in the field. The inversion stage is carried out with a mathematical approach to change the physical property model based on field data obtained from survey results. Inversion modeling uses *SimPEG* (Simulation and Parameter Estimation in Geophysics) (Cockett *et al*., 2015).

SimPEG is open source framework for inverse and forward modeling using potential data such as gravity, magentic, resistivity and EM method. The application of this framework in gravity modeling can be found at M *et al*. (2017) that use SimPEG to inverse model the Laguna del Maule volcanic system, as well in Bilqis & Zaky (2024) which utilize SimPEG for observing GDO (Generalized Derivative Operator) on synthetic model.

In this research, processing is carried out by utilizing synthetic data and gravity data in the Utah FORGE geothermal field in 2019 which focuses on processing and modeling subsurface 3D inversion using the python programming language by utilizing the *SimPEG* module. This research is expected to provide an overview of subsurface conditions based on the results of 3D inversion modeling and can identify the geological conditions of the Utah FORGE geothermal area.

REGIONAL GEOLOGY

The research area is in the FORGE field (Frontier Observatory for Research in Geothermal Energy) which is located approximately 322 km south of Salt Lake City and 16 km north of Milford, Utah. The Utah FORGE is located between the Basin and Range and the Colorado Plateaus (Moore, J et al., 2020). Scientific research on the FORGE field has been ongoing since the late 1970s. One of the aims of this research is for the development of geothermal fields in the Roosevelt Hot Springs area to enhanced geothermal system Utah, Milford.

The research area in Utah FORGE has a geomorphological structure dominated by alluvial and granitic deposits. The formation of a reservoir in this area is necessary for the development of EGS. The reservoir will be made by utilizing plutonic rocks of tertiary age originating from the center or core of the Mineral Mountains to the west. The distribution of plutonic rocks in the area is composed of the presence of diorite, granodiorite, quartz, syenite and granite with an age of 25.4 Ma – 8 Ma. The research was conducted in the Utah area, United States with research area boundaries as shown in **Figure 1**.

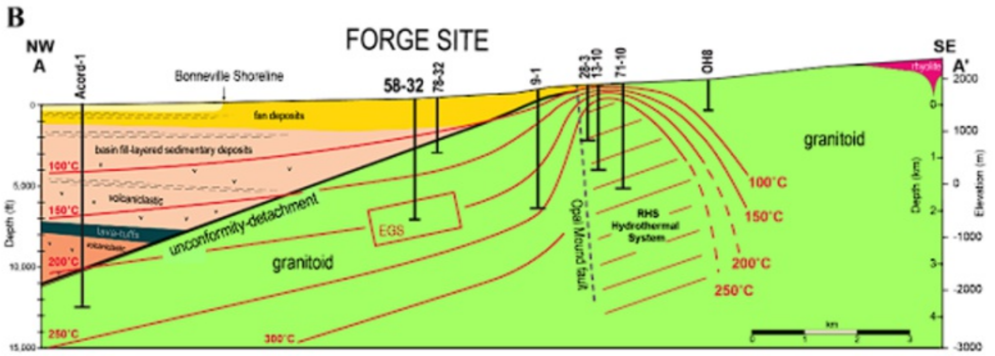

Figure 1. Lithological Information of the Research Area Based on Modeling Using Well Data 58-32 (Moore et al., 2020)

DATA AND METHODOLOGY

This research was conducted by utilizing gravity data measured in the Utah FORGE field, USA. This study is in the NAD83 coordinate system with UTM Zone 12N datum with area boundaries from 327000 - 342000 E and 4256000 - 4270000 N with a study area of about 15 km × 14 km (**Figure 2**). The data used in this study are synthetic data obtained from SimPEG 3D Gravity documentation of Utah FORGE secondary gravity data, United States downloaded through the Geothermal Data Repository website (*openei.org*).

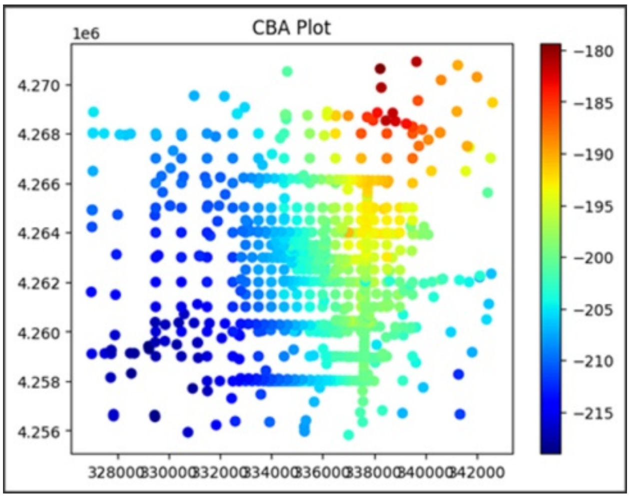

Figure 2. Complete Bouguer Anomaly of Utah FORGE.

The gravity data was collected from the Utah Geological Survey (UGS) as part of the FORGE project in 2019 with a total of 623 measurement points, the spacing between points ranging from 250 to 500 meters. In the data processing, the Bouguer density value obtained using the Parasnis method was 2.55 g/cm^3.

In addition, the elevation data (**Figure 3**) used in this research is Digital Elevation Model (DEM), data obtained from SRTM data that can be downloaded in the form of images with GeoTiff file types that have a resolution of 1 arc-second (90 meters).

The data processing and analysis stages were carried out using the Python programming language by utilizing available modules. The gridding process of Free Air Anomaly (FAA), elevation, and Complete Bouguer Anomaly (CBA) data was carried out using the ordinary kriging method available in the *pyKrige* module (Murphy et al., 2022) and the spline interpolation method using the *Verde* module (Uieda et al., 2016). While the 3D mesh design for gravity modeling is done using the discretize framework and SimPEG.

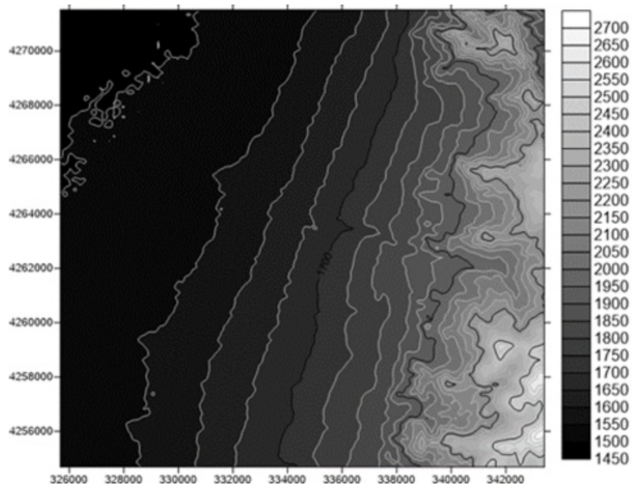

Figure 3. SRTM Digital Elevation Model (DEM) Data of the Research Area.

RESULT AND DISCUSSION

3D Inversion Results of CBA Utah, USA

The research was conducted by utilizing gravity data that has been corrected to get the complete Bouguer anomaly (**Figure 4**) value and anomaly separation has been carried out.

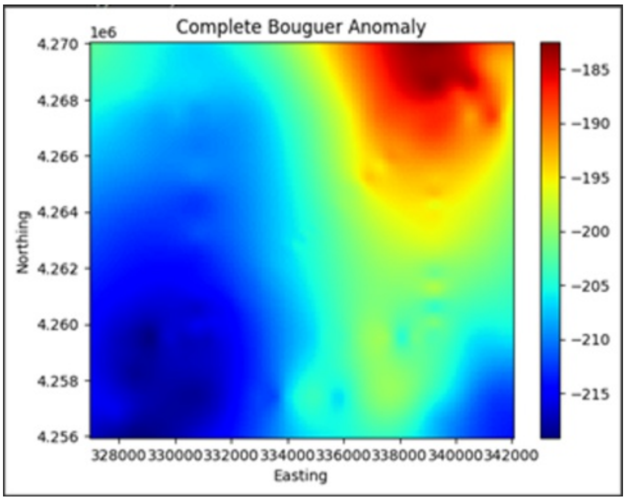

Figure 4. Gridding CBA Utah.

The **Figure 5** and **Figure 6** is the result of 3D inversion on cross sections A-A' and B-B'. Modelling was done by taking a section at an elevation of 1087.5 meters and at a depth of -1125 meters. In section A, which is oriented west to east of the study area, there is a relatively higher density contrast in the eastern part of the study area. Correlated with the geological data of the study area, it can be identified that the area is composed of granitoid components, rhyolite that thins towards the west. The anomalous contrast is likely caused by the difference in lithology of the Quaternary-aged deposits of the study area.

The anomaly slicing in **Figure 7** and **Figure 8** focuses on anomalies located in the South-West (SW) part of the study area. Section C-C' shows higher density contours in the Southeast part of the study area. When correlated with the Utah geologic map, the area is composed of rhyolite rocks and there are sedimentary inserts on the surface. Section D-D' has a relatively lower density contour and is identified as a quaternary age sedimentary deposit.

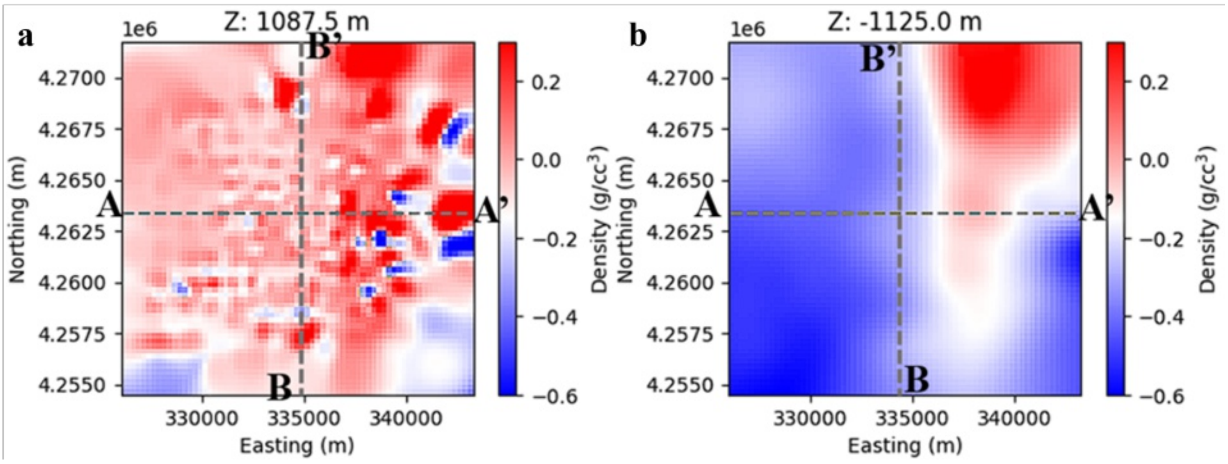

Figure 5. (a) Slicing A-A' and B-B' at Z = 1087.5 m; (b) Slicing A-A' and B-B' at Z = -1125.0 m.

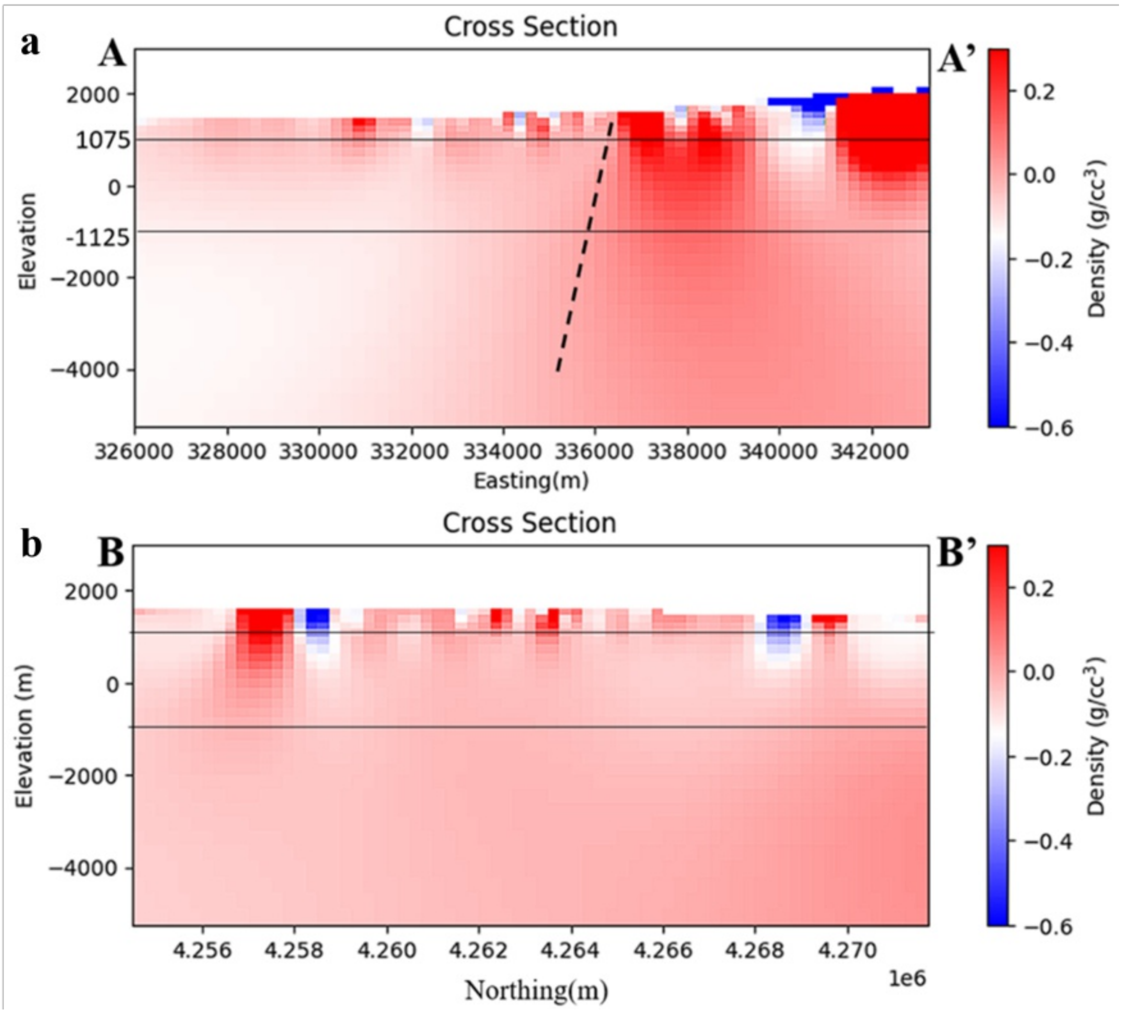

Figure 6. (a) Cross Section A-A'; (b) Cross Section B-B'.

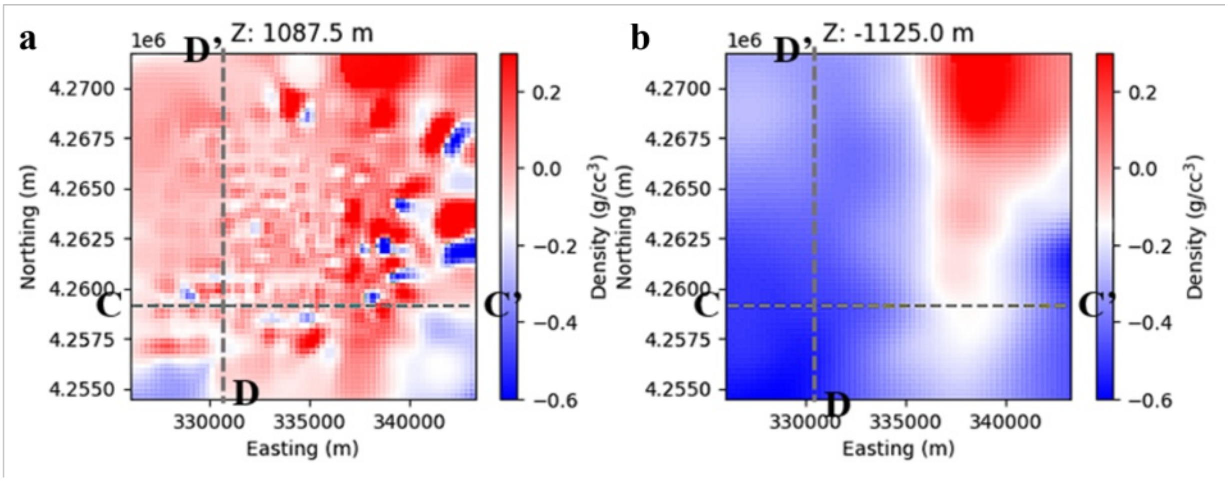

Figure 7. (a) Slicing C-C’ and D-D’ at Z = 1087.5 m; (b) Slicing C-C’ and D-D’ at Z = -1125.0 m.

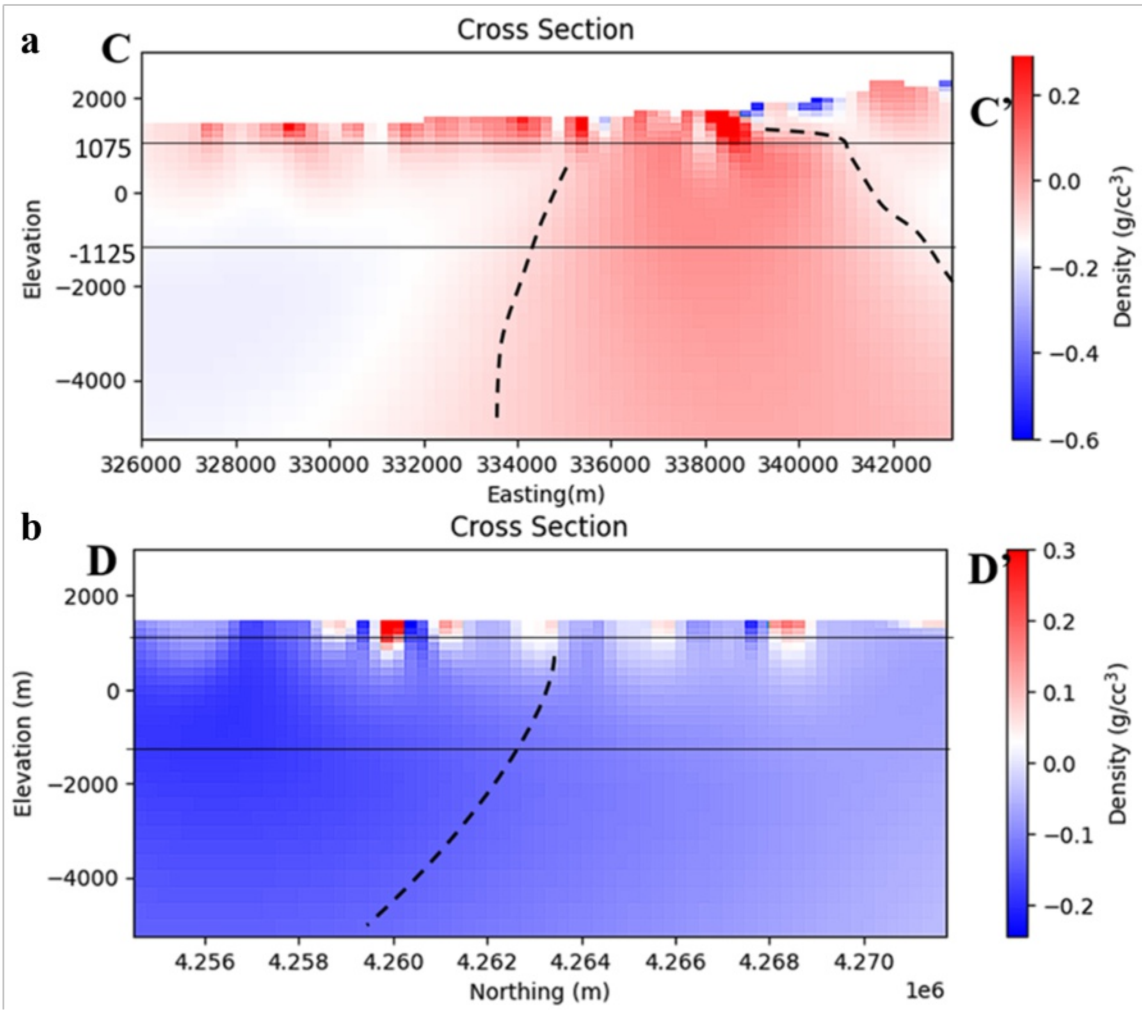

Figure 8. (a) Cross Section C-C’; (b) Cross Section D-D’.

Section E-E' and F-F' are in the northeastern part of the study area. The dominant sediments accumulated in the area are granitoids and diorites with a relatively higher density contrast compared to sediments in the southwest of the study area (**Figure 9** and **Figure 10**). Based on the results of gravity inversion in the section, it is estimated that it can be the location of the development of the Enhanced Geothermal System (EGS) in the Utah area.

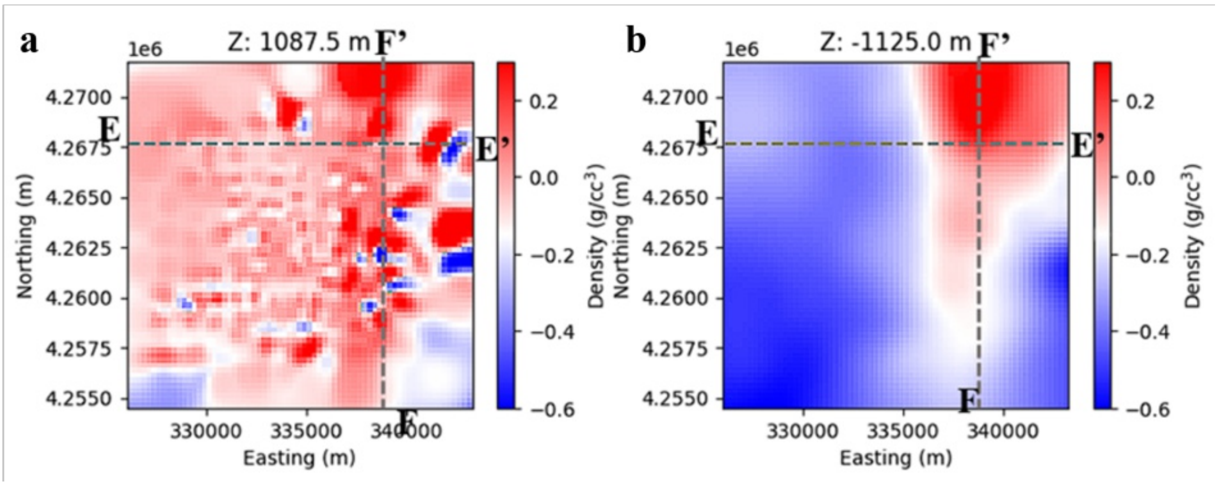

Figure 9. (a) Slicing E-E' and F-F' at Z = 1087.5 m; (b) Slicing E-E' and F-F' at Z = -1125.0 m.

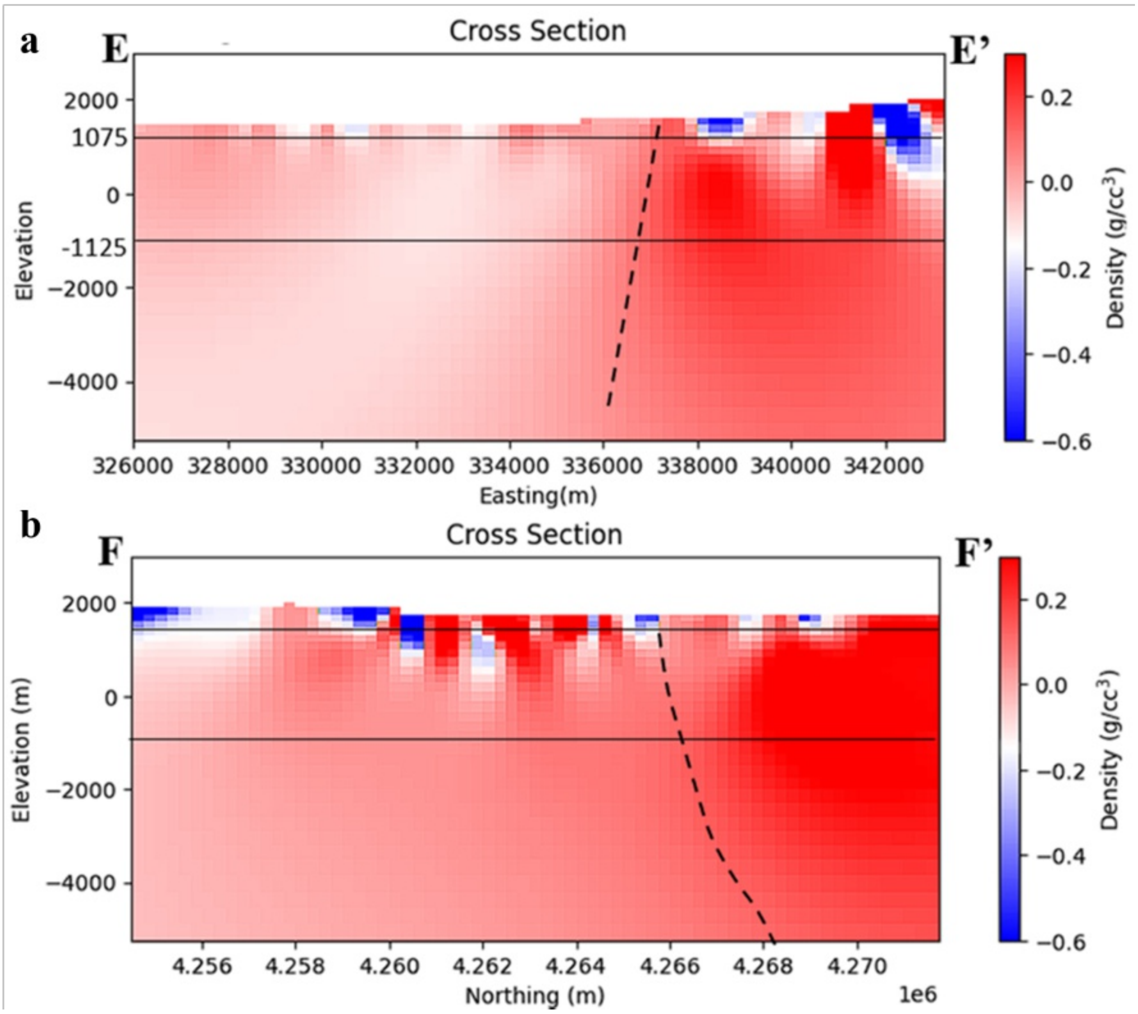

Figure 10. (a) Cross Section E-E'; (b) Cross Section F-F'.

3D Inversion of the 3rd Order Residual Utah, USA

Shallow anomaly analysis is also carried out by utilizing 3rd order residual anomaly data with a slicing model of 6 scattered covering the study area. The selection of 3rd order residuals is because the regional effects produced using 3rd order polynomials have shown the regional conditions of the CBA data. The residual results in **Figure 11** are expected to represent local variations in the research area.

The **Figure 12** and **Figure 13** is the result of 3d inversion modelling using residual anomaly data at positions Z = 950 meters and Z = -750 meters. Modelling using this residual anomaly is expected to display the shallow effect on the Utah field so that the mesh model only reaches a depth of 2000 meters below mean sea level.

The inversion results in section G-G' show a density contrast along the section which is estimated that the surface of the area is composed of alluvium and sediment deposits so that it has a relatively lower contrast compared to the east.

Cross sections K and L (**Figure 14** and **Figure 1**5) intersect in the southwest of the study area. The inversion results show a lower density contrast which is then correlated with the geological data of the study area. Section L-L' shows low density contrast which is identified as alluvium deposits.

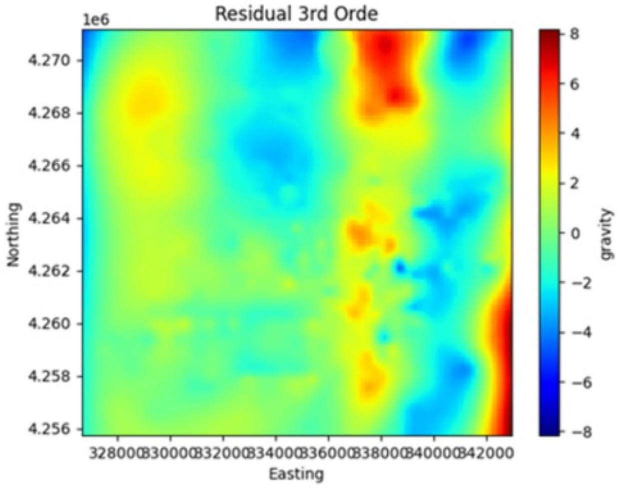

Figure 11. The 3rd Order Resisual of the Research Area.

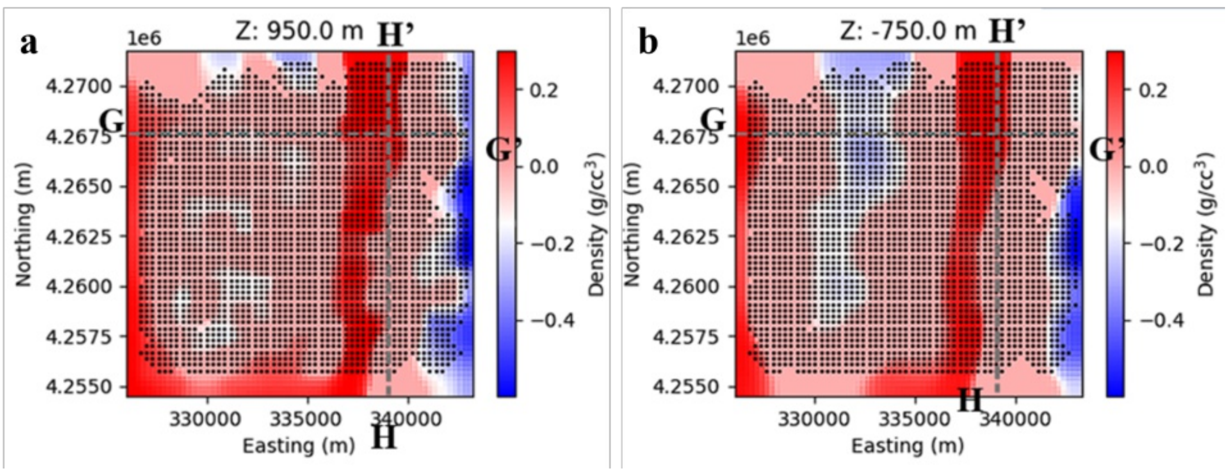

Figure 12. (a) Slicing G-G' and H-H' at Z = 950.0 m; (b) Slicing G-G' and H-H' at Z = -750.0 m.

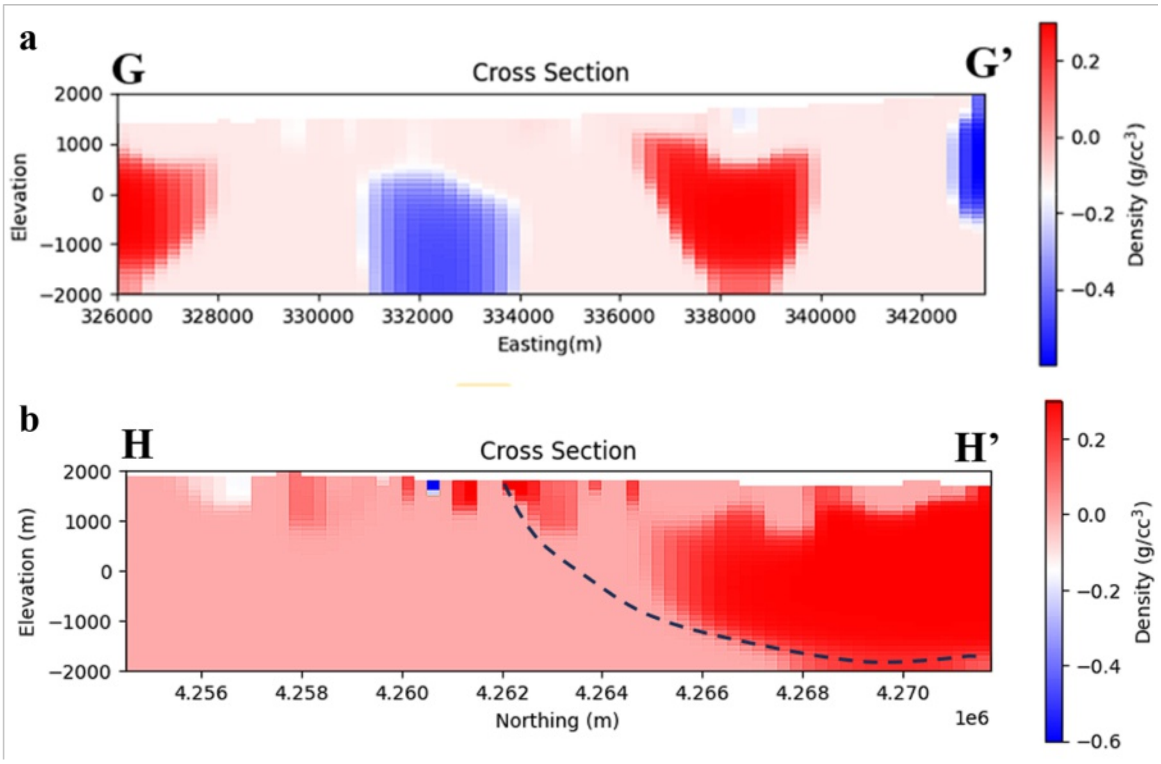

Figure 13. (a) Cross Section G-G'; (b) Cross Section H-H'.

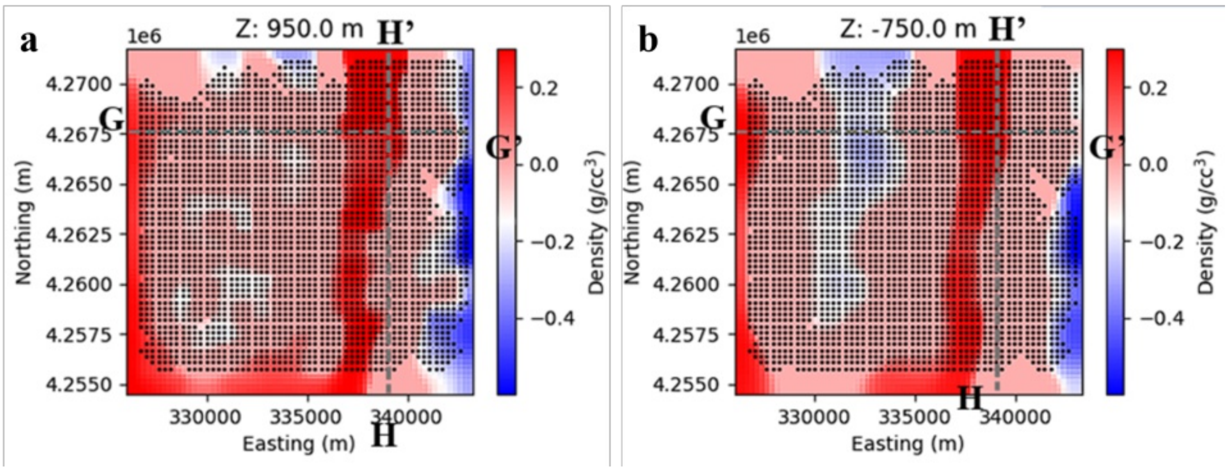

Figure 14. (a) Slicing K-K' and L-L' at Z = 950.0 m; (b) Slicing K-K' and L-L' at Z = -750.0 m.

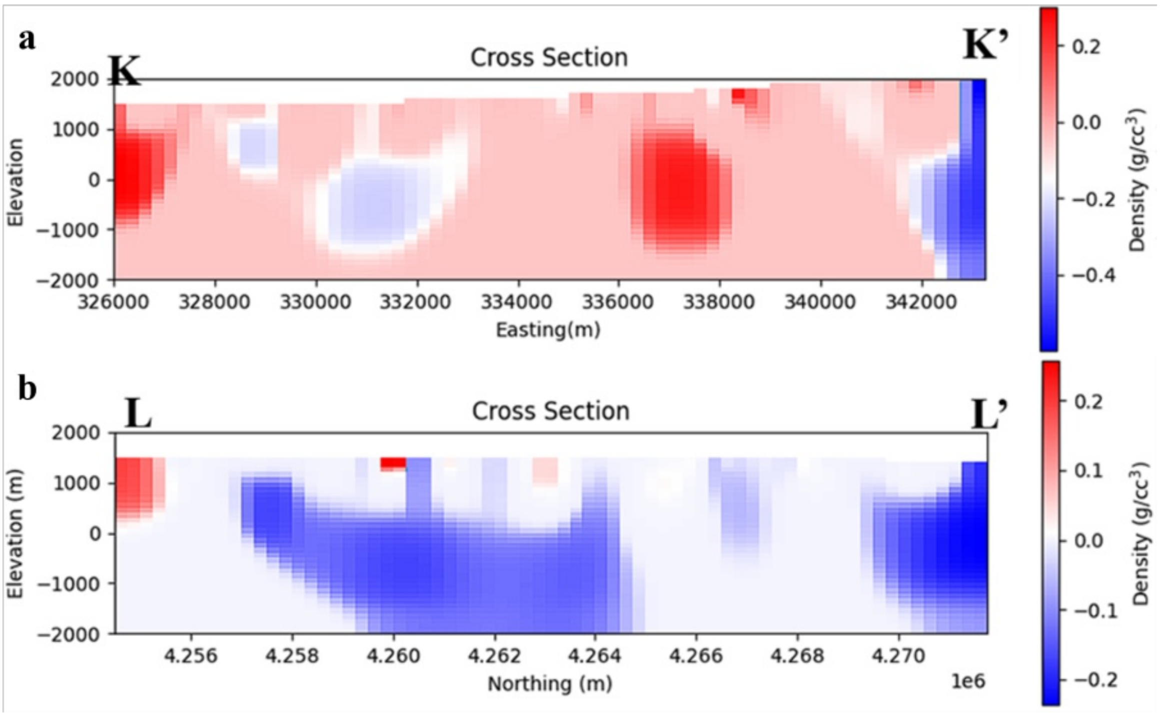

Figure 15. (a) Cross Section K-K'; (b) Cross Section L-L'.

CONCLUSION

Based on the research conducted, there are several conclusions obtained, namely, the results show the distribution pattern of the CBA anomaly (Complete Bouguer Anomaly) based on gridding using kriging and spline interpolation. In the Utah FORGE, United States research area interpolation using spline is better than using kriging because of the interpolation technique has a model that tends to be more flexible and assumes the spatial structure of data change with distance. However, the use of interpolation needs to be done with considering data.

Inversion modeling is done using a linear inversion method with sparse-norm regularization method so that it can help identify geological features that are clearer on geophysical data.

Based on the results of the Utah area research, a correlation was made between the inversion model results and the subsurface geological conditions. The high anomaly in the Northeast (NE) direction has a higher density than the low anomaly area in the Southwest (SW) direction which is composed of granitoid material.

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