Structural map of Sulawesi derives from gravity data and its implications for geothermal systems

Emi Prasetyawati Umar[1,3], *Agung* Harijoko[1], *Agung* Setianto[1] and *Wiwit* Suryanto[2*]

[1]Department of Geological Engineering, Gadjah Mada University, Yogyakarta 55281, Indonesia
[2]Department of Physics, Gadjah Mada University, Yogyakarta 55281, Indonesia
[3]Department of Mining Engineering, Universitas Muslim Indonesia, Makassar 90231, Indonesia

Abstract. Gravity satellites are one of the alternatives to conducting preliminary surveys because the cost of exploring a large area using conventional gravity methods is very expensive and takes a lot of time. Therefore, this study on Sulawesi Island uses a gravity satellite to identify fault contact boundaries. The methodology in this study consists of several steps, starting with a literature study, data collection through ICGEM, and then processing and analysis by compiling the gravity anomaly with the Sulawesi regional geological structure map, further interpreted using the classification of rock density variations from a geological perspective. The regional gravity anomaly values for Sulawesi Island and its surroundings range from -270.9 mgal to 320.8 mgal, averaging 78.99 mgal. High anomalies are estimated to be between 180 mgal and 360 mgal, dominated by land with a lithology predominance of igneous rocks, while low anomaly areas are identified in the Batui thrust subduction zone. This study concludes that the convergence of high and low gravity anomalies characterizes the fault contact boundary in the study area. This has implications for the geothermal system on Sulawesi Island, which has a significant impact as a medium for the release of hot fluids from the subsurface.

1 Introduction

Regionally, the geology of Sulawesi Island and its surroundings is very complex, and this is due to the divergence process of three lithospheric plates, namely the northward-moving Australian Plate, the westward-moving Pacific Plate, and the south-southeastward-moving Eurasian Plate. The Makassar Strait, which separates the Sunda platform (part of the Eurasian Plate) from the southern and central arms, was formed by the expansion of the sea floor spreading in the Miocene. The northward-moving Australian Continental Plate, the westward-moving Pacific Ocean Plate, and the relatively south-southeastward-moving Eurasian Continental Plate, Paleogene-aged subduction to the west followed by volcanic activity that produced volcanic rocks of the Bua Formation and Langi Formation (when it was still joined to Borneo). The separation of Sulawesi Island Borneo Island was caused by the rifting of the Makassar Strait which occurred in the Middle-Late Eocene [1-7].

The northern part of Sulawesi Island is the North Sulawesi Trench formed by the subduction process of the Sulawesi Sea oceanic crust. In the southeast arm, the convergence process occurs between the Southeast Arm and the northern part of the Banda Sea along the Tolo Thrust [8-9]. The Palu-Koro-Matano Fault System connects the two major structures (North Sulawesi Trough and Tolo Thrust).

Based on lithological associations and tectonic development, Sulawesi and its surrounding islands are *divided into five tectonic provinces, namely the West Sulawesi Tertiary Volcanic Arc, the Minahasa-Sangihe Quaternary Volcanic Arc, the Central Sulawesi Cretaceous-Paleogene Metamorphic Belt, the East Sulawesi Cretaceous Ophiolite Belt and its pelagic sedimentary associations, and the Banda Paleozoic Micro-continent fragment derived from the Australian Continent. The contact between the five provinces is a fault contact [10-15, 7]. Can be seen in Figure 1 Regional Geologic Map of Sulawesi Island.

Tectonic conditions on Sulawesi Island can trigger various kinds of geological disasters. However, these conditions are a gift in the availability of natural resources, including geothermal energy sources [16]. Geothermal is a process of transferring natural heat in the earth from the heat source to the reservoir, the heat transfer occurs by convection and conduction [17]. Geothermal potential can generally be seen from the appearance of manifestations on the surface. According to Wohletz and Heiken (1992) [18] geothermal manifestation is the release of geothermal fluid from the reservoir to the surface through fractures or permeable zones. Geothermal systems generally consist of three main elements, including (a) reservoir rocks that are (a)

* Corresponding author : ws@ugm.ac.id

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

permeable reservoir rock, (b) water to carry heat from the reservoir to the surface, and (c) heat source [19].

The tectonic conditions of Sulawesi Island are very complex, with geological structures in the form of faults that extend in various parts of the area of interest. The existence of several indicated active fault lines has implications for the presence of geothermal manifestations scattered in the region. The involvement of such complex geological structures in identifying geothermal systems through surface manifestations is needed in the linkage to gravity anomalies processed from gravity satellite data.

There are several methods that can be used in the initial identification of areas that have geothermal potential to support geological exploration, which involves identifying the condition of geological structures. For example, geological mapping is done by conducting field surveys. In addition, topographic mapping, with the help of technologies such as LIDAR (light detection and ranging), helps identify surface features related to geological structures. On the other hand, there are various conventional geophysical exploration methods for identifying geological structures in geothermal system identification, for example: the magnetic method by measuring the earth's magnetic field, the seismic method, the electromagnetic method, the resistivity method, and the gravity method used to identify mass variations and geological structures in the subsurface.

Though all of those methods can be used in mapping geological structures to identify implications for the presence of geothermal systems, all of those methods require a high operational cost in exploring a large area. In addition, the conventional methods require a lot of work effort and time in the process of completion. Meanwhile, those methods are considered less effective and efficient in their implementation for the preliminary identification of geothermal potential. Instead, the use of gravity satellites can provide solutions to these constraints because they are very practical and can be accessed from anywhere and anytime, as long as we have access to the internet.

Accordingly, gravity satellites can be used as one of the alternatives in preliminary studies for identifying geological structures that have implications for the occurrence of geothermal systems in large areas of geothermal potential. In their application, gravity measurements do not require direct contact with the ground. This allows data acquisition to be done by air or satellite. Gravity satellite surveys have been developed with data on the geographical position of measurement points on the surface [20–21].

There are many methods of accessing gravity satellite data, but the data was downloaded through the International Center for Global Earth Models (ICGEM) in this study. One of the reasons for choosing this access method is that through IGCEM, we can directly process the data through the system and immediately produce disturbance anomaly maps and gravity anomaly maps. Therefore, it can make the work more efficient and effective. The data obtained from IGCEM is used to map global gravity field anomalies on the surface by compiling regional geological structure data and areas with geothermal potential on Sulawesi Island. This study uses it to identify the contact boundaries of regional structures on Sulawesi Island in terms of gravity anomaly values. This study can also give us an overview of the role of geological structures in identifying the existence of geothermal systems that are active on Sulawesi Island.

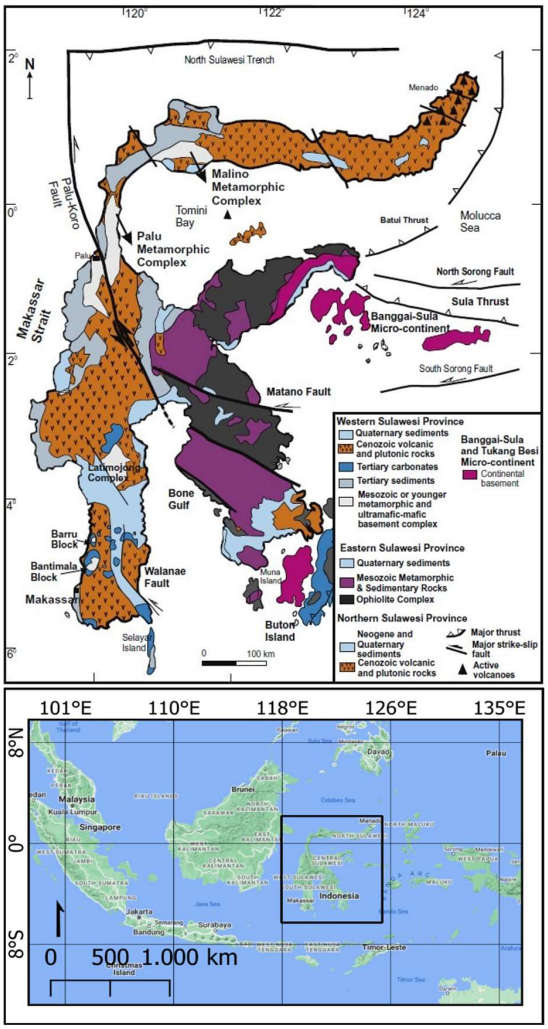


Fig. 1. Regional Geologic Map of Sulawesi Island, Indonesia [22-24].

2 Methodology

This research was conducted on Sulawesi Island, which has an astronomical location of 2°08′ N and 170°17′ E and an area of 174,600 km^2. The geographical location of Sulawesi Island consists of several seas and land boundaries. The seaboundaries of Sulawesi Island consist of the Flores Sea to the north, the Sulawesi Sea to the south, the Banda Sea to the east, and the Makassar Strait to the west. The land boundaries of Sulawesi Island include: to the north, the Philippines; to the south, the Nusa Tenggara Islands; to the east, the Maluku Islands; and to the west, Borneo Island.

The comparison of test results (orbit computation, GPS leveling, geostrophic current speeds) of this latest EIGEN model with GOCE-only models, EGM2008, GGM03, and GRACE-ITG2010S, illustrates the enhancement in precision at high degrees, while its performance remains indistinguishable from the recent GRACE-only model for low degrees. In comparison to the earlier iterations of EIGEN-6, this new iteration demonstrates a general advancement. GOCE processing carried out within this study was conducted within the framework of the European GOCE Gravity Consortium (EGG-C) under an ESA contract within the ESA GOCE High Level Processing Facility (GOCE-HPF). The resolution of the resulting spatial data is 0.1 degree, or equal to 11.1 km. This means that each piece of data taken represents a grid area of 11.1 km, which is approximately 11.1 km per pixel (11.1 km x 11.1 km). The data used on this regional scale is entirely adequate for mapping the gravity anomaly of Sulawesi Island.

Gravity satellite data is retrieved by downloading data for free through the International Center for Global Earth Models (ICGEM). EIGEN-6C4 can be accessed at the ICGEM data base at GFZ Potsdam (http://icgem.gfz-potsdam.de) with reference system WGS84. The data retrieved are gravity disturbance data and gravity anomalies. Through the ICGEM website, the data can be directly processed into disturbance gravity maps and gravity anomaly maps.

There are several steps involved in obtaining disturbance anomaly and gravity anomaly data by accessing the ICGEM website. The steps to access the disturbance anomaly data are as described below:

1. On the ICGEM Home menu, access the 'Calculation Service' menu, then click 'regular grids'. Afterwards, in 'Model Selection' in the 'Longtime Model' menu, select 'EIGEN-6C4'.
2. Furthermore, in the 'Functional Selection' menu, select 'gravity_disturbance'.
3. At the world map image on the right side of the 'Model Selection' menu, move the cursor to select the location that will be the study area. Afterwards, set the 'Grid Step [°]:' menu to 0.1 to get more detailed data.
4. Once everything has been set according to all the previous instructions (1, 2, 3, and 4), click the 'start calculation' button on the right side of the computer device screen. Wait for the system to open a 'new tab'.
5. The 'new tab' menu will automatically display data such as: functional, model, calculation start, calculation end, calculation time, grid, and reference system. The resulting map is a grid map and illumination model.

The steps that can be taken in accessing gravity anomaly data are the same as those in accessing disturbance anomaly data. The remaining steps are switched to step number 2 by accessing the 'Functional Selection' menu and switching the 'gravity_disturbance' menu to 'gravity_anomaly'.

The data obtained in the form of a gravity disturbance map and a gravity anomaly map provides information regarding the color gradation that distinguishes the gravity value.

The resulting maps were used to compile the re-digitized structural geology map of Sulawesi Island. The compiled maps were then interpreted using regional geological data in the form of structural and lithological data from Sulawesi Island and hot spring spots in areas with geothermal potential. Furthermore, to determine the variation in rock density among rock types in the research area, the classification of Telford (1990) was used (Figure 3).

Regional geological data and Sulawesi gravity anomaly data assist in identifying the contact boundary of the structure so that through these data, it can also provide an overview of the influence of structures in the existence of geothermal systems so that the distribution of hot springs on the surface appears. The steps and methodology of this study are shown in Figure 2.

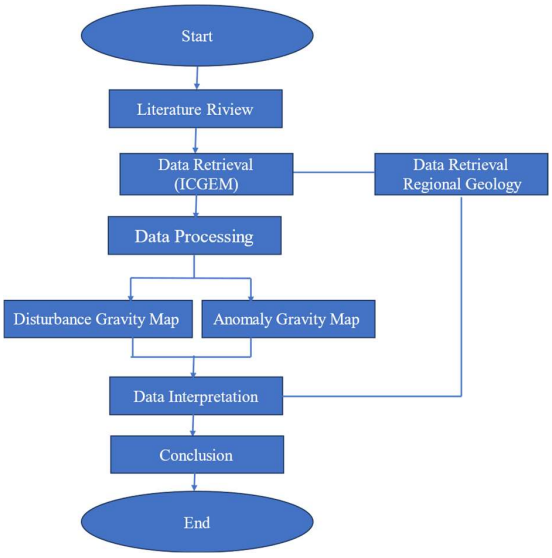


Fig. 2. Flowchart of Study.

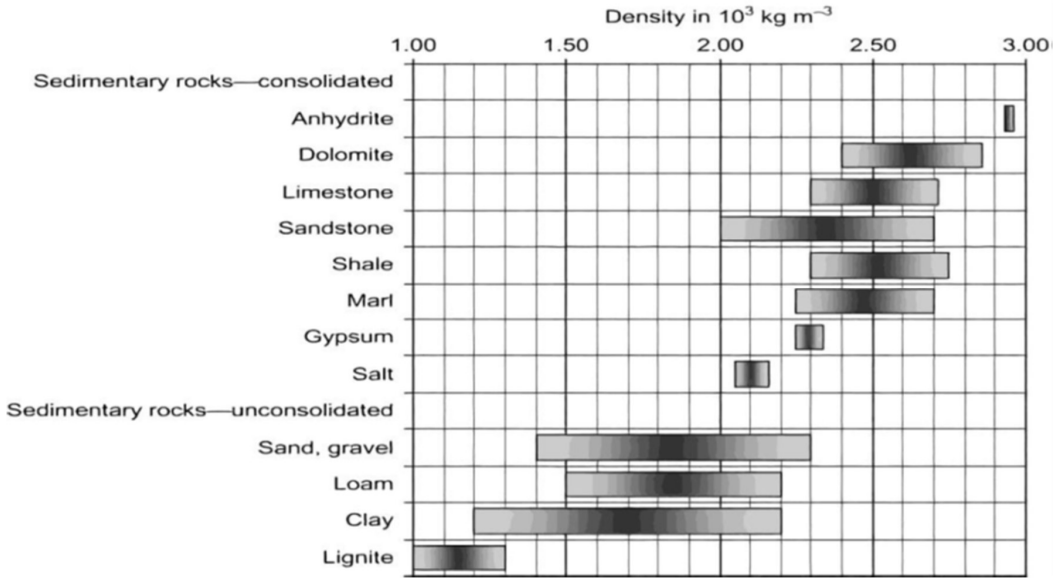


Fig. 3. Variation in rock density of rock types [26].

3 Result and discussion

The gravity method measures variations in the Earth's gravitational field caused by density differences, known as gravity anomalies [21]. Gravity data interpretation can provide a subsurface representation to interpret bedrock, lateral and vertical lithologic changes, and geological structures [25]. The various density constraints indicate that the subsurface structure is multifarious [26]. In addition, along with the development of technology, gravity data measurements from satellites have been developed, complete with data on the geographical position of the measuring point on the surface [27].

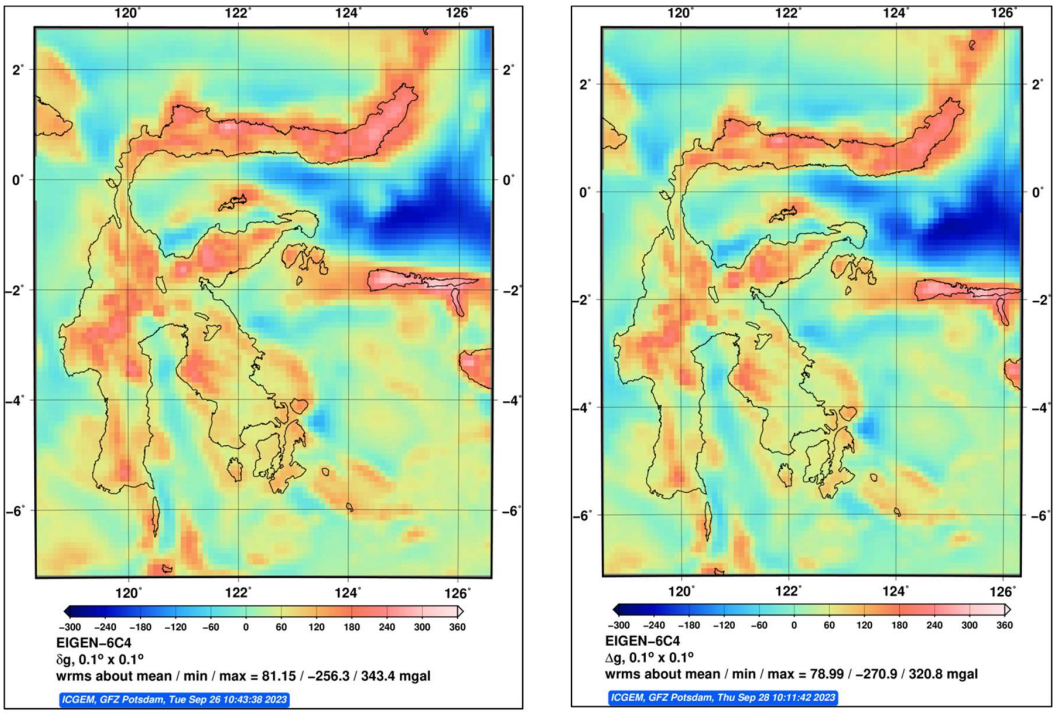
The application of satellites can help with measurement or data acquisition because climate, weather, topography, or geopolitical boundaries do not prevent it. This is due to the fact that satellite technology can cover larger areas, even isolated ones. Its operation is also sustainable, as satellites can provide measurement values with clearly recognized system parameters in a global coordinate system [28].

In this study, we tried to categorize the class ranges of disturbance and gravity anomalies in the study area. For high anomaly values range from 180 mgal - 360 mgal, medium 60 mgal - 179 mgal and low less than 60 mgal. This grouping is based on the range of gravity values from the data processing results automatically generated from the ICGEM (International Center for Global Earth Models) website. Then, we compiled the maps into the Sulawesi structure map and the geothermal potential map on Sulawesi Island, as shown in Figure 5.

The gravity disturbance and gravity anomaly maps (Figure 4) that have been compiled with the structure map and geothermal potential map of Sulawesi Island are then processed and layered to get the final result in the form of the Sulawesi Island Structure Map based on Disturbance Anomaly and the Sulawesi Island Structure Map based on Gravity Anomaly Value shown in Figure 5.

Regionally, the gravity disturbance value for Sulawesi Island and its surroundings ranges from -256.3 mgal to 343.4 mgal, averaging 81.15 mgal. The gravity anomaly regionally ranges from -270.9 mgal to 320.8 mgal, averaging 78.99 mgal. The high anomaly is estimated between 180 mgal and 360 mgal, which is dominated by the land area with the dominance of igneous rock lithology based on the regional lithology of the study area, which is located on the Sulawesi regional geological map (Figure 1). The low anomaly area is identified in the Batui thrust subduction zone range, with rock density values between -300 mgal and -270.9 mgal. The gravity anomaly of Sulawesi Island regionally ranges from -270.9 mgal to 320.8 mgal, with an average of 78.99 mgal.

The positive anomaly value indicates a higher density contrast than the surrounding rock's average density. Instead, the negative anomaly indicates a smaller difference in the density of the rock layers. These anomalies can be attributed to a combination of regional or residual anomalies in the subsurface that derive from differences in rock density between layers [21, 29]. Regional anomalies cover a wider range of levels compared to residual anomalies. In terms of depth, regional anomalies are located at deeper depths than residual anomalies, whereas noise is usually detected at shallower depths than residual anomalies [30-31].



(A.1) (A.2)

Fig. 4. (A.1) Map of Sulawesi Island Disturbance Anomaly Data Results from IGCEM (A.2) Map of Sulawesi Island Gravity Anomaly Data Results from IGCEM [33].

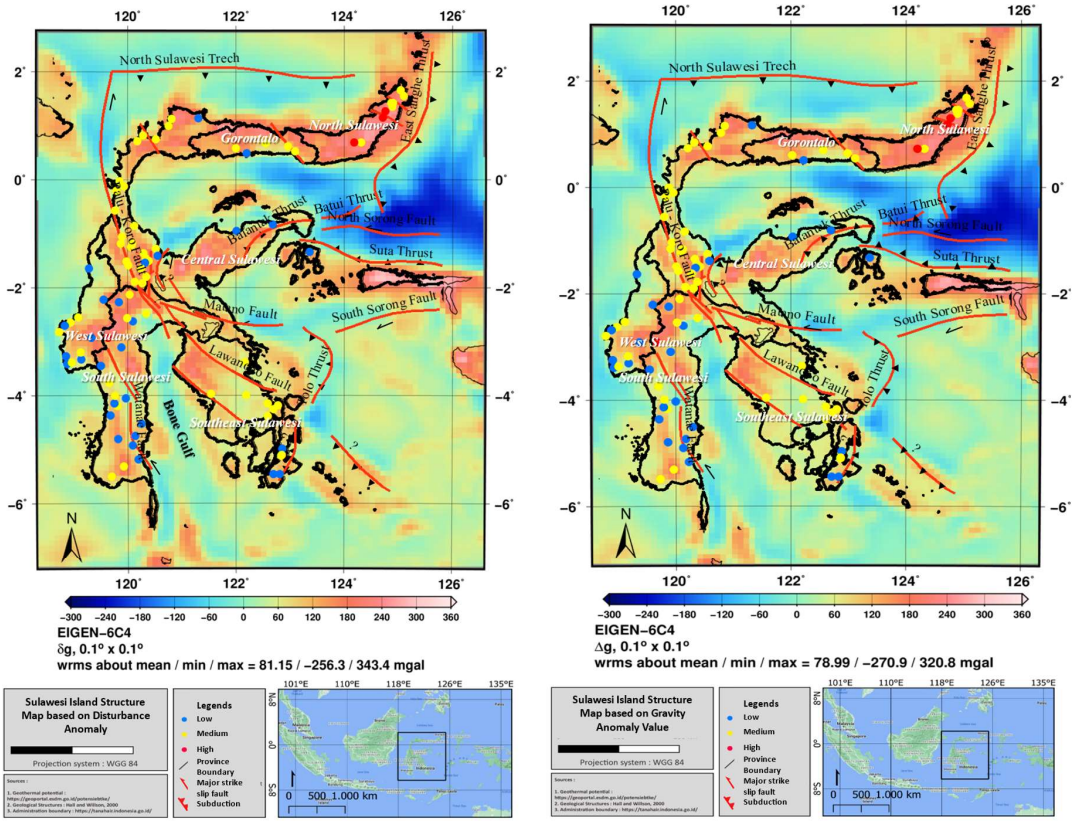


Fig. 5. Sulawesi Island Structure Map based on Disturbance Anomaly and Gravity Anomaly Value.

Regional anomalies refer to variations in the Earth's gravitational field caused by large subsurface mass distributions, such as geological formations or continental or oceanic expanses. These regional anomalies appear to arise from differences in the composition and distribution of mass in different layers of the Earth, including continental crusts and oceans, along with the rocks they contain. Such regional anomalies can facilitate mapping the geological structure and distribution of the continental crust and the oceans. However, it is important to recognize that these regional anomalies do not provide information about the details of local structures.

Residual anomalies refer to variations in the Earth's gravity field that remain after removing the effects of regional anomalies from the measured data. In this context, residual anomalies represent gravity field fluctuations arising from smaller or localized geological formations or structures. These anomalies occur due to differences in mass and density in the smaller or localized geological formations. The presence of residual anomalies helps in mapping and understanding smaller and localized geological structures. In addition, residual anomalies can provide valuable knowledge about the potential of natural resources, including geothermal potential. Differentiating regional anomalies from residual anomalies is very important in satellite gravity analysis because each provides different information about the structure and nature of the subsurface geology. By considering the two categories of anomalies together, a more comprehensive understanding of the geology of a particular region can be achieved [30].

According to Telford (1990) [26], many factors affect the density value of rocks, including rock composition, porosity, and fluid content in rocks. In addition to these factors, there is also the formation process, compaction during formation, depth of deposition, time of forming, and the degree of weathering that occurs in rocks. Intrusive igneous rocks have a higher value than lava and pyroclastic rocks. Furthermore, igneous rocks characterized by a base composition show a greater density value than acidic igneous rocks. The variations in the density value of each rock can be distinguished according to its type, as shown in Figure 2. In the interpretation process, the density value needs to be correlated with the existing geological information (Figure 1) to obtain more accurate gravity value modeling results.

Regionally high gravity anomaly values on Sulawesi Island indicate the lithology of volcanic rocks and plutonic rocks of the Cenozoic age; the gravity anomaly values range from 180 mgal to 360 mgal. Low-gravity anomalies are dominated by Quaternary sedimentary rocks with gravity values ranging from less than 60 mgal. It is obvious from the map results in Figure 5 that the contact boundary of regional structures is marked by the confluence of high and low gravity anomalies. These regional structures include Palu Koro Fault, Walanae Fault, Matano Fault, Lawanopo Fault, North Sorong Fault, South Sorong Fault, Batui Thrust, Balantak Thrust, Sula Thrust, Tolo Thrust, East Sangihe Thrust, and other unnamable faults.

The fault lines in the study area shown in Figure 5 indicate areas with hot springs. Hot springs are found along the faults and surrounding areas, such as the faults in South Sulawesi, Central Sulawesi, Southeast Sulawesi, North Sulawesi, and Gorontalo. These faults are assumed to control the presence of geothermal manifestations on the surface, with a meeting between high and low gravity anomalies [32, 34-36]. In addition, the compositing rocks in the presence of hot springs with high gravity anomalies are dominated by volcanic rocks.

Validation of mapping results with more comprehensive and detailed geological information is required. The results of this study can be utilized as preliminary information in knowing the geological structures that contribute to the occurrence of geothermal manifestations on the surface to support other research plans. Future researchers can conduct the same research using other methods (in addition to using data sourced from ICGEM) by comparing the results of this study and conducting further research in the form of more detailed three-dimensional (3D) modeling so as to provide new insights regarding the geological structures that evolved in the study area from various perspectives.

4 Conclusion

This study concludes that the regional gravity disturbance values for Sulawesi Island and its surroundings range from -256.3 mgal to 343.4 mgal, averaging 81.15 mgal. For gravity anomalies regionally ranging from -270.9 mgal to 320.8 mgal with an average of 78.99 mgal. High anomalies are estimated to be between 180 mgal and 360 mgal, dominated by land with a lithology predominance of volcanic rocks and plutonic rocks. Low-gravity anomalies are dominated by Quaternary sedimentary rocks with gravity values ranging from less than 60 mgal. Low anomaly areas identified in the Batui thrust subduction zone range from -300 mgal to -270.9 mgal.

The convergence of high and low gravity anomalies characterizes the fault contact boundary in the study area. This has implications for the geothermal system on Sulawesi Island, which has a significant impact as a medium for the release of hot fluids from the subsurface.

Concerning future researchers, the findings from this study can be used as preliminary data to understand the geological structures that contribute to the occurrence of geothermal manifestations at the surface. By comparing the findings of this study with additional research that is being conducted in the form of more meticulous three-dimensional (3D) modeling, future researchers can conduct similar studies using different techniques (other than using data from ICGEM) with the aim of providing new insights into the geological structures that developed in the study area from different perspectives.

References

1. R. W. Van Bellemen. The geology of Indonesia, Vol. IA: General geology of Indonesia and Adjacent Archipelagoes. Government Printing, The Hague. (1949)
2. J.A Katili. Past and present geotectonic position of Sulawesi, Indonesia.Tectonophysics **45**, 289–322 (1978)
3. W. Hamilton. Tectonics of the Indonesian region. In: U.S. Geological Survey Professional Papers. Department of Interior, U.S. Geological Survey, Reston, 345 (1979)
4. M. Villeneuve, R. Martini, H. Bellon, J.P. Réhault, J.J. Cornée, O.Bellier, S. Burhanuddin, F. Hinschberger, C. Honthaas, C. Monnier. Deciphering of six blocks of Gondwanan origin within Eastern Indonesia (South East Asia): Gondwana Research, **18**, 420–437 (2010). http://dx.doi.org/10.1016/j.gr.2009.12.011
5. T.M. Van Leeuwen, Muhardjo. Stratigraphy and tectonic setting of the Cretaceous and Paleogene volcanic-sedimentary successions in northwest Sulawesi, Indonesia: Implications for the Cenozoic evolution of Western and Northern Sulawesi: Journal of Asian Earth Sciences, **25**, 481–511 (2005) http://dx.doi.org/10.1016/j.jseaes.2004.05.004
6. T. Greenfield, A.C. Copley, C. Caplan, P. Supendi, S. Widiyantoro, N. Rawlinson. Crustal Deformation and Fault Strength of the Sulawesi Subduction Zone: Tectonics, **40**, 1-18 (2021) http://dx.doi.org/10.1029/2020TC006573
7. A.M.S. Nugraha, R. Hall, M. BouDagher-Fadel. The Celebes Molasse: A revised Neogene stratigraphy for Sulawesi, Indonesia. Journal of Asian Earth Sciences **228**, 1-28 (2022) https://doi.org/10.1016/j.jseaes.2022.105140
8. E.A .Silver, R. McCaffrey, R.B. Smith. Collision, Rotation, and the Initiation of Subduction in the Evolution of Sulawesi, Indonesia: Journal of Geophysical Research, **88**, 9407–9418. (1983) https://doi.org/10.1029/JB088iB11p09407
9. R. Hall, M.E.J. Wilson. Neogene sutures in eastern Indonesia: Journal of Asian Earth Sciences, **18**, 781–808 (2000) http://dx.doi.org/10.1016/S1367-9120(00)00040-7
10. T.O. Simandjuntak. Neogene tectonics and Orogenesis Indonesia. Bulletin of the Geological Society of Malaysia. **33**, 43-64 (1993) https://doi.org/10.7186/bgsm33199305
11. W. Hamilton. Tectonics of the Indonesian region. In: U.S. Geological Survey Professional Papers. Department of Interior, U.S. Geological Survey, Reston, 345 (1979)
12. O. Bellier, M. Sébrier, D. Seward, T. Beaudouin, M. Villeneuve, E. Putranto. Fission track and fault kinematics analyses for new insight into the Late Cenozoic tectonic regime changes in West-Central Sulawesi (Indonesia): Tectonophysics, **413**, 201–220 (2006) http://dx.doi.org/10.1016/J.TECTO.2005.10.036
13. P. Molnar, K.E. Dayem. Major intracontinental strike-slip faults and contrasts in lithospheric strength: Geosphere, **6**, 444–467 (2010) http://dx.doi.org/10.1130/GES00519.1
14. T.R. Charlton. Tertiary evolution of the Eastern Indonesia collision complex: Journal of Asian Earth Sciences, **18**, 603–631 (2000) http://dx.doi.org/10.1016/S1367-9120(99)00049-8
15. M.E.J. Wilson, D.W.J. Bosence, A. Limbong. Tertiary syntectonic carbonate platform development in Indonesia. Sedimentology **47**, 395–419 (2000) https://doi.org/10.1046/J.13653091.2000.00299.X
16. M.P. Hochstein, S. Sudarman. History of geothermal exploration in Indonesia from 1970 to 2000. Geothermics, **37**, 220–266 (2008) http://dx.doi.org/:10.1016/j.geothermics.2008.01.001
17. M.P. Hochstein, P.R. Browne. Surface manifestations of geothermal systems with volcanic heat sources. Encyclopedia of Volcanoes," ed: Academic Press, USA. (2000)
18. K. Wohletz, G. Heiken. Volcanology and Geothermal Energy. Berkeley, California: University of California Press. (1992) http://ark.cdlib.org/ark:/13030/ft6v19p151/
19. F. Goff, C.J. Janik. Geothermal systems, Encyclopedia of Volcanoes, Academic Press, New York, USA. (2000)
20. C. Hirt, S. Claessens, T. Fecher, M. Kuhn, R. Pail, M. Rexer. New ultra-high resolution picture of Earth's gravity field. Section 2. (2013) https://doi.org/10.1002/grl.50838.New
21. W.J. Hinze, R.R.B. Von Frese, A.H. Saad. Gravity and Magnetic Exploration. Camridge University Press. (2013)
22. R. Hall. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations. J. Asian Earth Sci. **20**, 353–431 (2002) https://doi.org/10.1016/S1367-9120(01)00069-4
23. A. Kadarusman, S. Miyashita, S. Maruyama, C.D. Parkinson, A. Ishikawa. Petrology, geochemistry and paleogeographic reconstruction of the East Sulawesi Ophiolite, Indonesia. Tectonophysics **392**, 55–83 (2004) https://doi.org/10.1016/j.tecto.2004.04.008

24. A. Maulana. Petrology, Geochemistry and Metamorphic Evolution of the South Sulawesi Basement Rocks Complexes, Indonesia M.Phil. thesis. Australian National University, Canberra, 215 (2009)
25. F. J. F. Ferreira, J. de Souza, A. de B. e. S. Bongiolo & L. G. de Castro. Enhancement of the total horizontal gradient of magnetic anomalies using the tilt angle. Geophysics, **78**, J33–J41 (2013) https://doi.org/10.1190/geo2011-0441.1
26. M. Telford. Applied geophysics, **127**, Issue 3212, 783–785. Cambridge University Press. USA. (1990) https://doi.org/10.1038/127783a0
27. J. M. Reynolds. An Introduction to Applied and Environmental Geophysics (2nd Editio, Issue 606). John Wiley & Sons, Ltd. Wiley-Blackwell. (2011)
28. D.B. Chelton, J.C. Ries, B.J. Haines, L.L. Fu, P.S. Callahan. Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications. International Geophysics Series. Academic Press. **69**, 1-131 (2001)
29. Y. Shandini, P.A. Kouske, S. Nguiya, M.P. Marcelin. Structural setting of the Koum sedimentary basin (North Cameroon) derived from EGM2008 gravity field interpretation. Sciendo, **48** (2018) https://doi.org/10.2478/congeo-2018-0013
30. H. Abidin. Peranan Geodesi Satelit Dalam Memahami Dinamika Bumi di Wilayah Indonesia. Artikel, 50 (2008)
31. F. Barthelmes. Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models Theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM). Scientific Technical Report STR09/02 Revised Edition, January 2013 (2013). ISSN 1610-0956. http://icgem.gfz-potsdam.de http://dx.doi.org/10.2312/GFZ.b103-0902-26
32. R. Lewerissa, S. Sismanto, A. Setiawan, S. Pramumijoyo. The igneous rock intrusion beneath ambon and seram islands, eastern Indonesia, based on the integration of gravity and magnetic inversion: Its implications for geothermal energy resources. Turkish Journal of Earth Sciences, **29**, 596–616 (2020) https://doi.org/10.3906/yer-1908-17
33. The calculation service of the International Centre for Global Earth Models (ICGEM). http://icgem.gfz-potsdam.de
34. B. Legowo, R. Nailatunisrina, H. Purwanto, B. Purnama, W. Suryanto. *Modelling of Volcano Lawu Fault Structure Using Gravity Anomaly to Determine Landslides Potential*, IOP Conference Proceedings, **986** (2022) https://dx.doi.org/10.1088/1755-1315/986/1/012025
35. E.P. Umar, Jamaluddin, A. Nawir, M.A. Massinai, M.F.I. Massinai, Anshariah. *Geochemical characterization of thermal water springs in Barasanga field, North Konawe, Southeast Sulawesi,* AIP Conference Proceedings, **2595**, (2023) https://doi.org/10.1063/5.0124383
36. E.P. Umar, H. Anwar, J.R. Husain, S. Muharni, Jamaluddin, M.A. Massinai. Pengaruh Struktur Geologi terhadap Kemunculan Mata Air Panas Daerah Sulili Pinrang Sulawesi Selatan. Jurnal Geocelebes, **4**, 41-45 (2020). 2595, 050017, (2023) https://doi.org/10.20956/geocelebes.v4i1.9542