Journal Of Geophysics
April 2024, Vol. XLV No. 2

# Delineation of Subsurface Geological Structures in Meghalaya, Northeast India using Gravity Gradients Analysis

**[1]Muthyala Prasad*, [2]Chandra Prakash Dubey, [1]Mulavada Vidyasagar, [3]Sangem Satheesh**

*[1]Central Ground Water Board, Guwahati-781035, India, [2]Department of Geology and Geophysics, IIT Kharagpur-721302, India, [3]Centre of Exploration Geophysics, Osmania University, Hyderabad-500007, India*
**E-mail*: prasadgoud333@gmail.com

## Abstract

Understanding subsurface structures in Meghalaya, Northeast India, is crucial for elucidating the region's geological framework. This paper aims to identify geological features, particularly lineaments that influence geo-hazards in the area. To achieve this, we employed various qualitative interpretation techniques on gravity anomaly data, revealing several key geological structures. The Bouguer anomalies, ranging from 39mGal to 107mGal, predominantly exhibit positive values, indicative of active deformation and mantle uplift beneath the Shillong Plateau. Power spectral analysis of the gravity data identified two average depth sources at approximately 26 km and 4 km, corresponding to mid-crustal and upper-crustal levels, respectively as depicted in aeromagnetic studies. Further, the gravity gradients, $G_{zx}, G_{zy}$ *and* $G_{zz}$ revealed many lineaments and structural trends in EW, NS, NE-SW and NW-SE directions. These trends coincide with the regional tectonic fabric highlighting their significant impact on subsurface geology. Additionally, the peak gravity signatures in analytical signal map delineated geological structures suggesting the fault zones or lineaments in the study area. It is suggested, therefore, the lineaments identified from Satellite Bouguer anomaly data using various qualitative interpretation techniques offer valuable insights into the region's seismotectonic activity to enhance the evaluation of tectonic dynamics and forecast the geological hazards.

*Key words* Geological structures, Meghalaya, Gravity anomaly, Qualitative Interpretation

## 1. Introduction

The identification and characterization of subsurface geological structures are fundamental to geophysical exploration, with critical applications in natural resource exploration, environmental studies, and understanding geological hazards. Among various geophysical methods, gravity surveying is particularly effective in mapping subsurface density variations indicative of different geological formations. These surveys measure variations in the Earth's gravitational field caused by density differences in subsurface materials, which can be attributed to varying rock types, voids, mineral deposits, and other geological structures. By analyzing these variations, geophysicists can infer the distribution and characteristics of subsurface structures, providing valuable insights into the geological composition of an area.

Meghalaya, located on the Shillong Plateau in north-eastern India, is a seismotectonically active region due to the ongoing Indian-Eurasian convergence and uplift since the Cenozoic era Vernant et al., 2014; Kumar et al., 2015; Najman et al., 2016; Agrawal et al., 2022. This region presents a challenging environment for subsurface exploration because of its extreme and unique conditions. Geographically, Meghalaya lies between 25.03°N to 26.12°N latitude and 89.82°E to 92.81°E longitude. Physiographically, it represents a remnant of an ancient plateau of the Precambrian Peninsular shield, block-lifted to its present elevation Raghukanth et al, 2011. The Plateau is bounded by the Brahmaputra graben filled with alluvium to the north, the Dawki fault to the south, the Naga thrust to the east, and the Yamuna fault to the west Kayal et al, 2010, Islam et al, 2011. Some researchers have described the major lineaments, structural trends, faults, and fracture systems in the study area based on field studies and Landsat imagery Valdiya, 1976, Mazumder, 1976, Parthasarathi, 1978; Gupta and Sen, 1988; Srinivasan, 2003, Biswas and Grasemann, 2005, Duarah and Phukan, 2011, GSI; Mishra, 2019 and the references therein.

Earlier several researchers have conducted to understand the mass distribution due to Crustal movement and the relationship between tectonics and gravity Verma and Gupta, 1973. Positive gravity values are observed over the Shillong Plateau and negative values over the Brahmaputra Valley Verma and Mukhopadhyay, 1977.

Aeromagnetic surveys have identified several structural patterns favourablefor mineral prospecting Sharma et al, 2012. Based on the gravity and magnetic analysis of the Shillong Plateau, subsurface structures have been delineated, indicating potential mineral resources and tectonic activity Syiem et al., 2014.

However, the correlation between geophysical features and structural characteristics, as well as their importance in seismotectonic activity, is not well understood. Therefore, the present study aims to delineate the significant geological structures associated with tectonic activity in the Meghalaya Plateau. By analyzing gravity data, we can reveal density variations and map the underlying geological formations. This method offers a promising approach to investigating the complex subsurface geology of the region. Understanding these subsurface structures is crucial for several reasons it aids in identifying potential resource deposits, assessing geological hazards, and managing environmental risks.

## 2. Geological Setting and Tectonic Framework of the Shillong Plateau

The Shillong Plateau, located in north-eastern India, is a significant geological and tectonic feature of the Indian subcontinent. The plateau is situated within a complex tectonic regime and is bounded by a set of fault systems along its periphery and within its interior Seeber et al., 1981; Halder et al., 2022. The compounded effect of the peripheral faults, linked with the Himalayan and Indo-Burmese orogenies, has uplifted the plateau, making it the only raised block in the entire Himalayan foreland Najman et al., 2016. This uplift has resulted in notable elevation differences between the Shillong Plateau and both the BrahmaputraValley to the north and the Bangladesh plains to the south.

Geology of Meghalaya Fig. 1 is diverse, with formations ranging from late Cenozoic alluvialfills to unclassified gneissic complexes from the Archean to Paleoproterozoic eras Strong et al., 2019. About 44% of the area consists of these gneissic complexes, overlain by sediments and greenstones of the Shillong Group Mishra, 2019. The region is primarily composed of Precambrian rocks, including Archean and Proterozoic granites, gneisses, and schists Kumar and Gupta, 2010. The Metasedimentary Shillong Group, dating from 1.53Ga to 1.55Ga Mitra, 1998, Devi and Sarma, 2010, along with igneous rocks, porphyritic granites, and ultramafic alkaline-carbonate complexes Evans, 1964, Mishra and Sen, 2001, represent some of the oldest geological formations in India.The plateau also features sedimentary deposits from the Paleozoic and Mesozoic eras, including sandstones and shales accumulated over various geological periods Mukhopadhyay, 2000. Extensive karst topography, due to high rainfall and limestone dissolution, creates a landscape with caves, sinkholes, and underground rivers Sarkar and Ray, 2012.

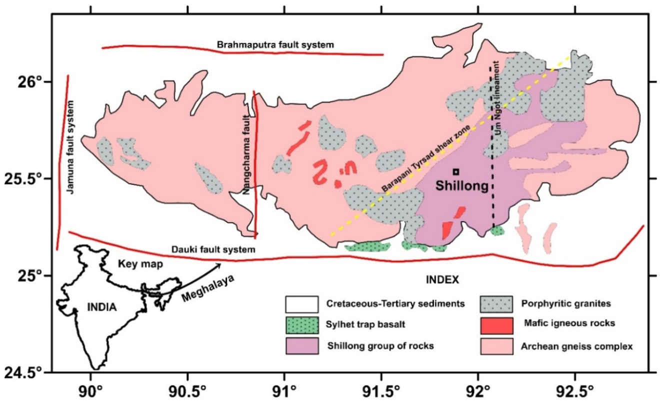

*Fig.1.Regional geology and tectonic map of Meghalaya modified after Islam et al. 2014*

The tectonic framework of the Shillong Plateau is influenced by the convergence between the Indian and Eurasian Plates, significantly impacting its geological structure. This activity has resulted in uplift and block-faulting Jain and Saxena, 2004. Major tectonic boundaries in the ShillongPlateau dissected by major E–W, N–S, and NW–SE oriented faults Brahmaputra fault, Jamuna fault, Nongchram Fault, Um Ngot lineaments, Barapani–Tyrsad shear zone Fig. 1 relatedto tectonic forces from both the Himalayan collision zone and the Indo-Burma subduction zoneKayal 2001, Islam et al. 2011.

The plateau's central area, characterized by higher topographic features, is tectonically active and structurally weak Duarah and Phukan, 2011. It continues to move northeast due to intense compressional tectonism, with rapid shortening and higher convergence rates in the eastern segment of the Indian Plate Harijan et al, 2003, Banerjee et al, 2008.

## 3. Data and Methodology

### 3.1 Datasets

In the present study area, characterized by mountainous terrain and dense vegetation, ground-based gravity acquisition is challenging. To overcome these difficulties, we utilized various types of open sources data.

#### 3.1.1 Topography

Topographical information was obtained from Open Topography, which provides global bathymetry and topography grids based on the latest SRTM + digital elevation model DEM with a spatial resolution of 15 arc seconds Tozer et al, 2019, 2024. The topographic map Fig.2 displays mountains and high plateaus with elevations ranging from 0 to 1933 meters, clearly depicting all major topographic features of the study region. The Shillong Plateau, located in the Himalayan foreland, features raised topography composed of crystalline basement rocks partially overlain by sedimentary deposits from the Cretaceous to Miocene periods Strong et al, 2019.

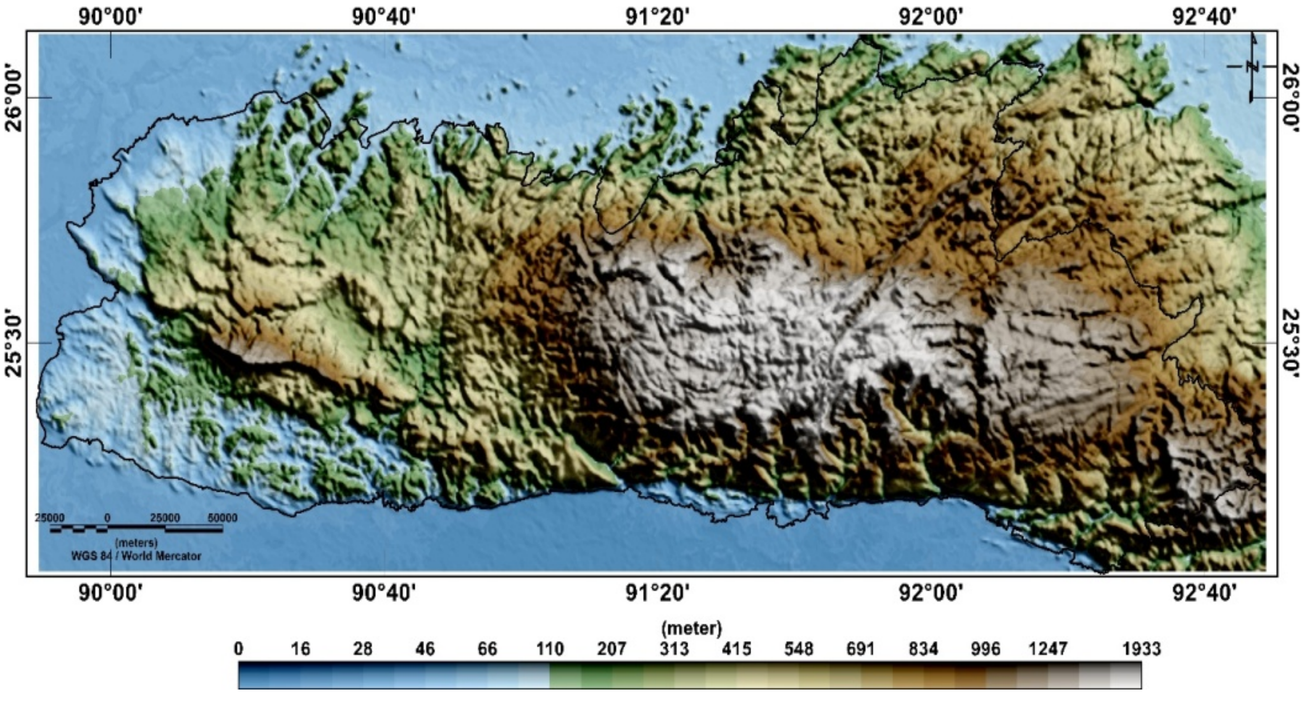


***Fig. 2:*** *The Topographic map of Meghalaya* https//opentopography.org/

### 3.1.2 Satellite derived gravity model

For gravity data, we utilized free-air and Bouguer anomaly data derived from satellite observations provided by the World Gravity Model WGM2012. This high-resolution grid of gravity anomalies 2′ × 2′ is based on a combination of global gravity models, including EGM2008 and DTU10 Bonvalot et al., 2012. WGM2012 is accessible via the Bureau Gravimetrique International BGI official website https//bgi.obs-mip.fr/data-products/gravity-databases/land-gravity-data/.

The BGI currently offers the most precise information on the Earth's gravity field at short wavelengths, providing an excellent complement to airborne and satellite gravity measurements. The free-air anomalies Fig. 3 range from -67mGal to 205mGal and show a positive correlation with topography. The Bouguer anomalies Fig.4 are predominantly positive, varying between 39mGal and 107mGal.

## 3.2 Methodology

### 3.2.1 Power Spectrum

Power spectral analysis of gravity and magnetic data is a widely used technique for estimating the depth of geological features Spector and Grant, 1970. This method involves determining the depth of geological sources from the data by applying a wavelength filtering technique that uses radially averaged power spectra. The term "radially averaged" refers to averaging power values for waves of the same wavelength. To estimate the average depth of these sources, the slope of the power spectral curves is smoothed, and the results are applied to equation 1.

$$Depth = \frac{-slope}{4\pi} \quad \text{..................(1)}$$

### 3.2.2 Gravity gradients

Gravity gradients are highly effective for identifying and delineating the edges of geological features such as faults, folds, and lineaments. Measurements of gravity gradients offer greater sensitivity to variations in subsurface density compared to traditional gravity measurements. This is because gravity gradients detect changes in the gravitational field over shorter distances, making it easier to identify subtle variations in subsurface structures. This enhanced sensitivity is particularly useful for revealing small-scale structures and providing insights into the geometry of anomalies that might be overlooked with standard gravity data. In the present study, we analyzed how gravity varies spatially, focusing on the components $G_{zx}$, $G_{zy}$, and $G_{zz}$. The individual components and their combinations offer valuable information about subsurface characteristics Dubey et al., 2014; Dubey and Tiwari, 2017.

### 3.2.3 Analytical Signal

The analytic signal technique, also known as the total gradient method, was described in detail Nabighian, 1972. This technique is commonly used to analyze potential field anomalies to determine the boundaries/edges signal is defined as the sum of the square root of the square of the two horizontal derivatives and the vertical derivatives of the gravity/magnetic field. The corresponding amplitude of the analytical signal $AS\ (x, y)$ given by

$$|AS\ x,y| = \sqrt{\left(\frac{\partial G_{zx}}{\partial x}\right)^2 + \left(\frac{\partial G_{zy}}{\partial y}\right)^2 + \left(\frac{\partial G_{zz}}{\partial z}\right)^2} \quad \ldots \quad 2$$

where $G_z$ is the gravitational field observed at $(x, y)$, $\frac{\partial G_{zx}}{\partial x}, \frac{\partial G_{zy}}{\partial y}$ are the partial horizontal derivatives and $\frac{\partial G_{zz}}{\partial z}$ is vertical derivative.

## 4. Results and Discussion

The positive and negative free-air anomalies shown in Fig.3 reflect the complex topography and subsurface variations of Meghalaya. These anomalies highlight regions with elevated and depressed gravitational fields, which are likely associated with the area's geological and geomorphological characteristics.

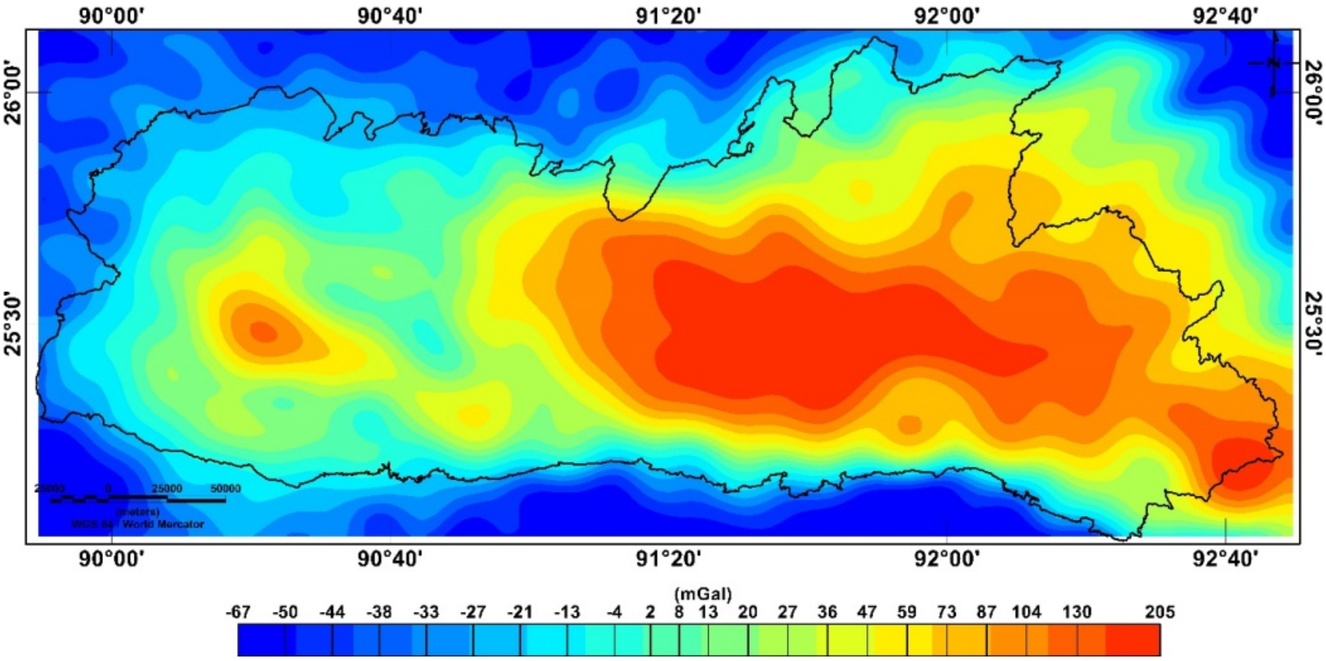


*Fig.3:* *The free air anomaly map of Meghalaya*

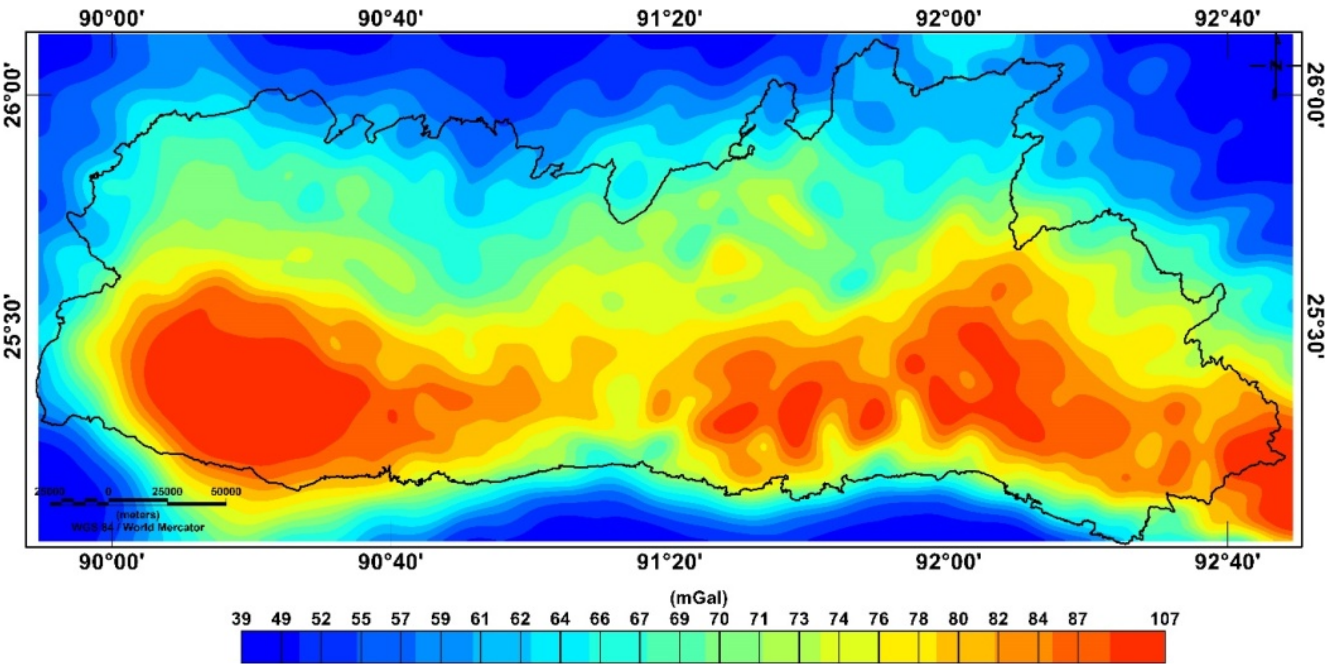


*Fig.4:* *The Bouguer anomaly map of Meghalaya*

The eastern region, in particular, exhibits the most pronounced positive anomalies, ranging from 100mGal to 205mGal. The Bouguer anomaly map of Meghalaya Fig.4, reveals significant variations in the gravitational field, which indicate diverse geological structures and tectonic activities across the region. The map shows an overall anomaly variation of 71mGal. In the northern part of the area, minimum anomalies range from 39mGal to 65mGal, while the southern part exhibits the strongest positive anomalies, ranging kfrom 75mGal to 107mGal. The decreasing trend of gravity values towards the north suggests a deepening basement, thickening of Quaternary sediments, or the presence of low-density materials in the subsurface. Conversely, the south-eastern region displays high gravity responses, which are likely to be attributed to the presence of older metamorphic rocks and various rock types from the Assam–Meghalaya gneissic complex Ashish et al, 2024. The black dashed lines on the map denote a total of 24 identified lineaments, which are linear features potentially corresponding to geological structures such as faults or fractures. These lineaments are oriented in various directions, primarily E–W, N–S, NE–SW, and NW–SE, representing the oldest set and forming the major structural framework of the Precambrian terrain Mishra, 2019. These lineaments often align with the transition zones between 'high' and 'low' anomaly regions, suggesting the presence of fault zones or fracture systems that influence the distribution of geological units and regional topography. Additionally, delineating several fault systems, lineaments, and shear zones highlights significant density contrasts revealed in previous studies Srinivasava and Sinha, 2004, Saha et al, 2010, Islam et al, 2014 and the references therein. To validate these observations, several qualitative techniques were applied, including Gradients $G_{zx}, G_{zy} and\ G_{zz}$, and Analytic Signal method. The radially averaged power spectrum of gravity data has been computed Fig. 5. The power spectrum reveals two distinct segments, each fitted with regression lines Spector and Grant, 1970, Mishra and Kumar, 2012, Prasad et al, 2021, Prasad and Dubey, 2023. From the slopes of these regression lines, average depths to various gravity sources have been calculated, yielding interface depths of 26 km and 4 km Fig.5.

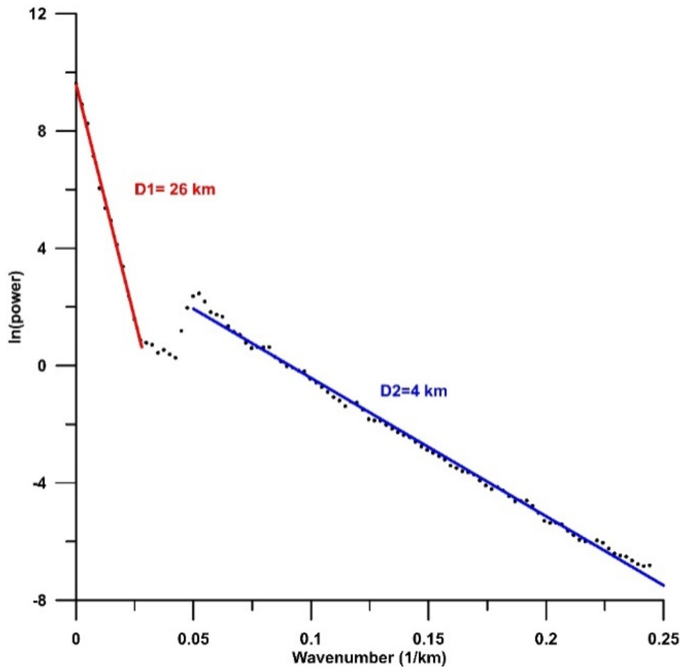


***Fig. 5:*** *Radially averaged power spectrum of gravity anomaly map*

The observed offset at the intersection of the regression lines corresponding to depths of 26 km and 4 km in the gravity anomaly spectrum is likely to be influenced by the resolution of the gravity data or wavelength discontinuities. The depths are consistent with aeromagnetic signatures reported by Sharma et al. 2012, who estimated a deeper layer at approximately 25 km and an intermediate layer at about 4 km. The deeper source at 26 km, likely represents a mid-crustal depth and the shallower source at 4 km indicates an upper crustal depth. This interpretation is consistent with both the gravity and aeromagnetic data, providing valuable insights into the geological structure of the region Rajasekhar and Mishra, 2008.

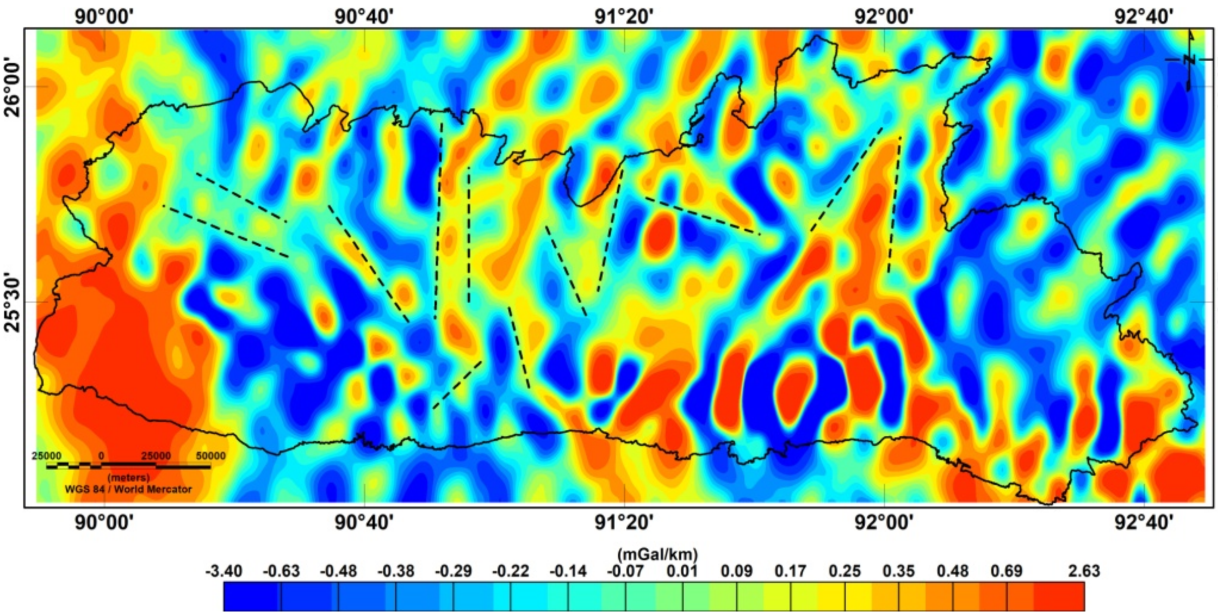


***Fig. 6:*** *Gravity gradient $G_{zx}$ map of the study area - Lineaments identified in the current study are highlighted with dashed black lines.*

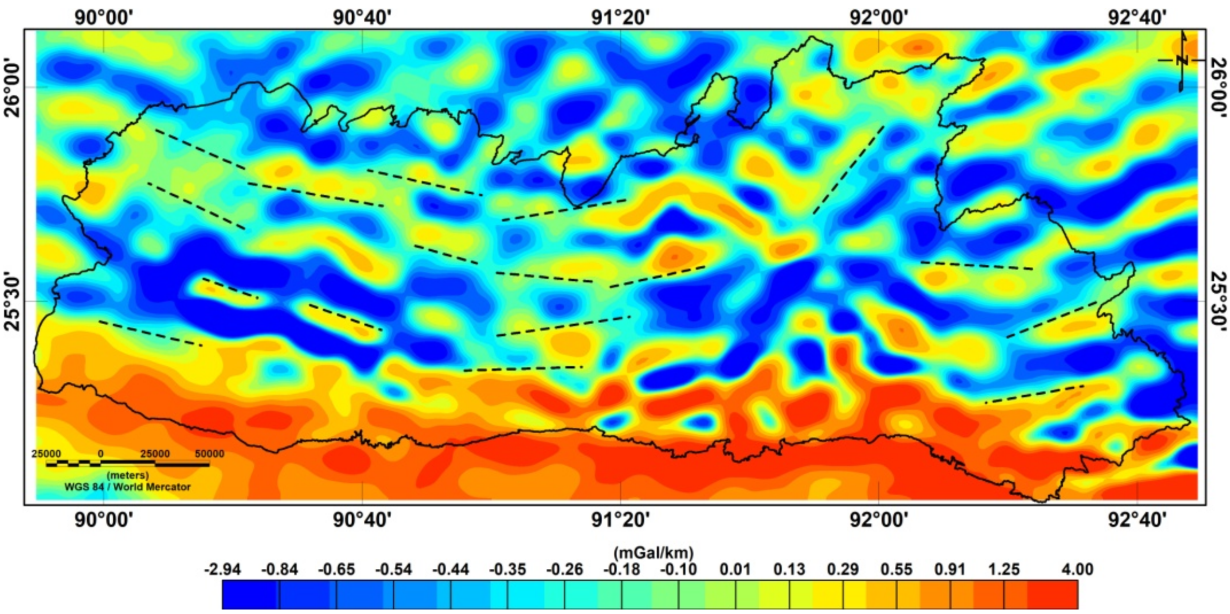


***Fig. 7:*** *Gravity gradient $G_{zy}$ map of the study area - Lineaments identified in the current study are highlighted with dashed black lines.*

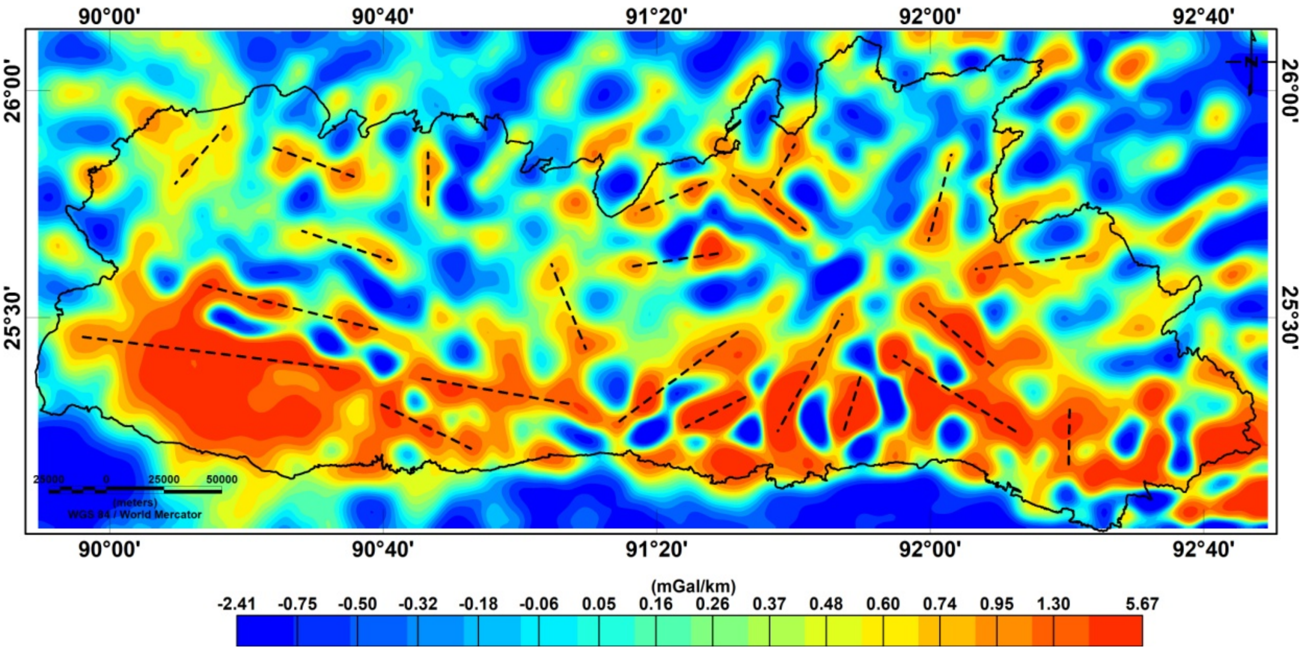


***Fig.8:*** *Gravity gradient $G_{zz}$ map of the study area - Lineaments identified in the current study are highlighted with dashed black lines.*

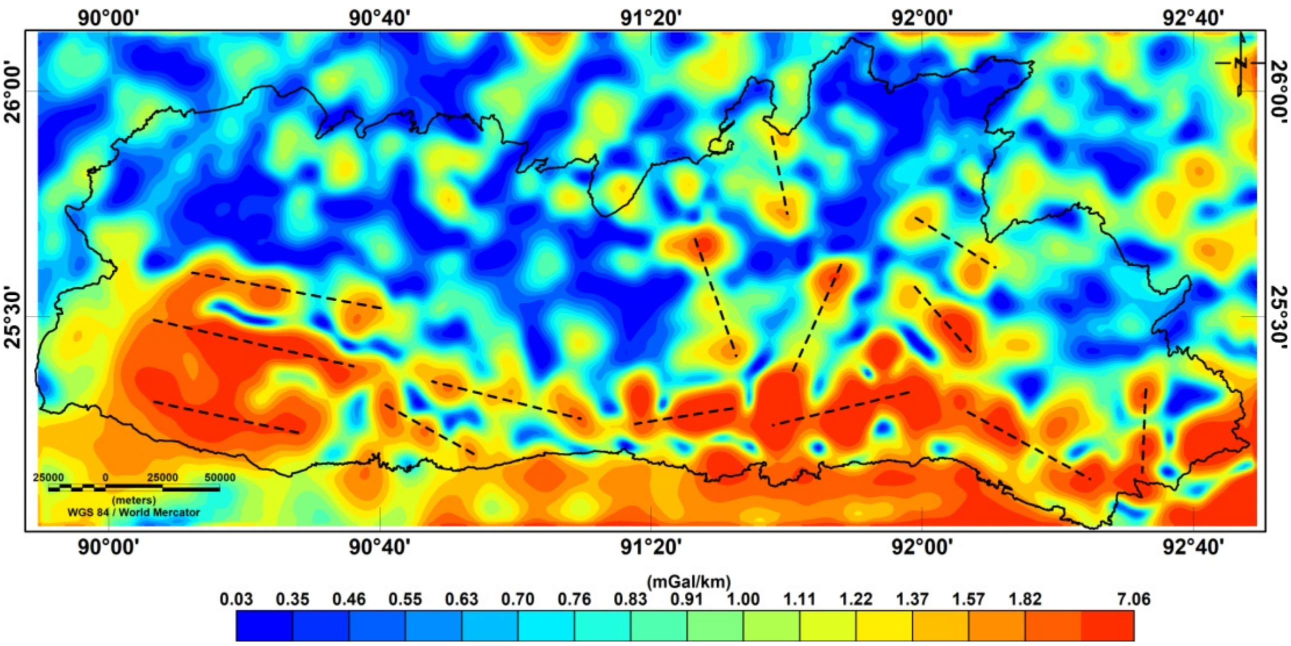


***Fig.9:*** *Analytical signal Amplitude map of Meghalaya - Lineaments identified in the current study are highlighted with dashed black lines*

Different geological structures can produce distinct signatures in gravity gradients. By analyzing the spatial distribution and orientation of these anomalies, we have identified lineaments beneath the study area, as depicted in Figures 6, 7and 8. The $G_{zx}$ map Fig.6 shows intermediate signatures ranging from -0.50mGal to 0.70mGal/km in the central region. In contrast, the northern and southern parts of the area exhibit the highest positive and negative anomalies, which distinctly highlight several lineaments oriented in various directions. Similar patterns are observed in both the $G_{zy}$map Fig.7 and the $G_{zz}$ map Fig.8.

The Analytical signal map Fig.9 reflecting positive amplitudes primarily in the southern part of the study area, with signatures-oriented NW-SE, and W-E. The high gravity peak of analytical signal highlights the edges of contacts/lineaments/ faults and causative sources Telford et al, 1990, Blakely, 1996, Kumar et al, 2018. In contrast, the northern region displays the negatives anomalies. The map also delineates various geological structures and trends, illustrating the orientations and distributions of different structural features across the study area. The Meghalaya state boundary shows the largest positive anomalies in the southern part and the largest negative anomalies in the northern part. The significant anomaly contracts may suggest that the edges of the sources may represent faults, lineaments, or fractures. The dashed black lines on this map represent probable lineaments, interpreted based on the patterns of anomalies. This technique sharpens the peaks of gravity anomaly signals and broadens weaker signals, making it effective for locating deep sources. The analysis of gravity anomalies, combined with various qualitative techniques, enables the identification of lineaments that correlate well with longitudinal profiles of rivers and geomorphic indices Mishra, 2019. The development of these geological structures is clearly influenced by regional tectonics.

## 5. Conclusion

In this study, satellite-derived gravity data were analyzed and interpreted using various mathematical techniques, which led to the delineation of several lineaments associated with potential lithological structures in Meghalaya, Northeast India. Positive Bouguer anomalies in the study area may suggest active deformation and uplift of the mantle beneath the plateau. Power spectral analysis of gravity data indicates two primary depth sources at approximately 26 km and 4 km, correlating with mid-crustal and upper crustal depths, consistent with previous aeromagnetic studies. Gravity gradient analyses $G_{zx}, G_{zy} and G_{zz}$ highlight the distinct lineaments and structural trends, predominantly oriented in E-W, N-S, NE-SW, and NW-SE directions, corroborating with previous studies. These orientations align with regional tectonic features, indicating their significant influence on the subsurface geology. Further, Analytical signal mapalso delineates geological structures, with high positive amplitudes corresponding to potential fault zones or lineaments. This can enhance the understanding of potential geological hazards and improve the assessment of tectonic dynamics. However, further studies are needed to achieve a more comprehensive understanding of the region.

## 6. Acknowledgements

The authors wish to express their sincere gratitude to the Chairman and Members of the Central Ground Water Board CGWB, Faridabad, and to the Regional Director of CGWB, NER, for granting permission to publish this work. We are also deeply grateful to the anonymous reviewers for their valuable comments and suggestions, which have significantly enhanced the quality of this manuscript. Additionally, we extend our heartfelt thanks to the Bureau Gravimetrique International BGI for providing the high-resolution gravity data for this study.

## References

Agrawal P, Misra A, Aand Srivastava A. 2022 Cenozoic uplift and deformation of the Shillong Plateau, north-eastern India, Implications for the Himalaya-Burma convergence zone. Jour.of Asian Earth Scie. 230, 104583.

Al-Badani F and Al-WathafY., 2018, Analytical signal method for interpretation of gravity and magnetic data. Jour. of Applied Geophysics, V.155, pp. 140-151.

Ashish V, Kumar R, and Pandey S., 2024, Gravity and magnetic analysis of the Shillong Plateau. Geophysical Journal International V. 235, pp. 1212-1230.

Banerjee P, Burgmann R, Nagarajan B, and Apel E, 2008, Intraplate deformation of the Indian subcontinent. Geophysical Rese. Letters, 3518 L18301.

Biswas S and Grasemann B., 2005, Tectonic setting and fault kinematics of the Shillong Plateau, northeast India. Journal of Asian Earth Sciences, V. 252 133-145.

Blakely R.J., 1995, 1996, Potential Theory in Gravity and Magnetic Applications. CambridgeUniversity Press.

Bonvalot S, Balmino G, Briais A, Kuhn M, Peyrefitte A, Vales N,and Gabalda G 2012, World Gravity Map WGM 2012. Bureau Gravimétrique International BGI.

Devi N, and Sarma J., 2010, Geological evolution of the Shillong Plateau A
review. Geological Society of India Special Publication V. 2, pp. 75-89.

Duarah B and Phukan P2011 Structural geology and tectonics of the Shillong Plateau. Geological Society of India, V. 753., pp. 499-514.

Dubey C.P, Götze H.J, Schmidt S and Tiwari V.M2014 A 3D model of the Wathlingen salt dome in the North west German Basin from joint modelling of gravity, gravity gradient, and curvature. Interpretation, *2*4 SJ103-SJ115.

Dubey C.P, Tiwari V.M. and Rao P.R., 2017, Insights into the lurking structures and related intraplate earthquakes in the region of Bay of Bengal using gravity and full gravity gradient tensor. Pure and Applied Geophysics, V.174, pp. 4357-4368.

Evans P., 1964, The tectonic framework of Assam. Journal of the Geological Society of India V.52, pp.80-96.

Gupta H.K, and Sen P, 1988, Seismicity of the Shillong Plateau and its tectonic implications. Tectonophysics, V.1411, pp. 3225-237.

Halder K, Kundu B and Gupta S, 2022., Tectonic deformation and seismic hazard in the Shillong Plateau, NE India. Journal of Geodynamics, 147, 101892.

Harijan S, Bhattacharyya A and Gupta, H. K., 2003, Stress field and seismotectonics of the Shillong Plateau. Tectonophysics, 3691-2 113-127.

Islam M.R, Ahmed N, and Mahanta B., 2011, Structural and tectonic evolution of the Shillong Plateau. Jour. of Geological Society of India, V.785, pp. 381-392.

Islam M.S, Meshesha D and Shinjo R., 2014, Mantle source characterization of Sylhet Traps, north-eastern India A petrological and geochemical study. Jour. of Earth System Scie. V.123, pp. 1839-1855.

Jain A.K, and SaxenaV.K., 2004, Seismicity and active tectonics of the Shillong Plateau. Journal of Asian Earth Sciences, V.233, pp. 181-191.

Kayal J.R., 2001 Microearthquake activity in some parts of the Shillong Plateau. Current Science, V.812, pp. 163-168.

Kayal J.R, De R, Das Pand Mukhopadhyay S., 2010, Shillong Plateau Seismotectonics and earthquake hazard assessment. Geological Society of India Special Publication, 75 159-172.

Kumar M, and Gupta S., 2010, Precambrian geology of the Shillong Plateau. Geological Survey of India Special Publication, V.5, pp. 45-63.

Kumar R, SinghR.P and Gupta S., 2018, Analytical signal method for geological boundary detection. Geophysical Prospecting V.661, pp. 195-209.

Mazumder D., 1976, Structural geology and tectonics of the Shillong Plateau. Geological Society of India Special Publication V.15, pp. 85-95.

Mishra S and Sen S., 2001, Geological evolution and tectonics of the Shillong Plateau. Jour. of the Geological Society of India, V.585, p. 399-407.

Mishra M.N., 2019, Active tectonic deformation of the Shillong Plateau, India Inferences from river profiles and stream-gradients. Jour. of Asian Earth Scie..181, 103904.

Mitra S., 1998, Geology and tectonics of the Shillong Plateau. Geological Society of India Special Publication, V.21, pp. 1-16.

Mukhopadhyay M., 2000, Structural and tectonic framework of the Shillong Plateau. Geological Survey of India Special Publication, V. 57, pp. 45-63.

Najman Y, Oliver G and Walther M., 2016, Uplift and deformation of the Shillong

Plateau. Jour. of Asian Earth Scie. V.134, pp. 205-222.

Parthasarathi G., 1978, Geomorphology and tectonics of the Shillong Plateau. Jour. of the Geological Society of India, V.192, pp. 93-103.

Prasad M and Dubey C.P., 2023, Tectonic and structural elements of Southern Granulite Terrane, South India Inferences from gravity and magnetic studies. Jour. of Asian Earth Scie. 256, 105823

Prasad M, Dubey C.P, Joshi K.B, and Tiwari V.M., 2021, Crustal density and susceptibility structure beneath Achankovil shear zone, India. Lithosphere, 2021Special 6.

Rajasekhar R.P and Mishra D.C., 2008, Crustal structure of BengalBasin and Shillong Plateau Extension of Eastern Ghat and Satpura Mobile Belts to Himalayan fronts and seismotectonics. Gondwana Research, V.143, pp. 523-534.

Raghukanth S.T.G, Ghosh S. K, and Mahajan, A.K., 2011, Seismotectonic framework of the Shillong Plateau. Jour. of Seismology, V.153, pp. 333-346.

Saha D, Bhattacharya A and BasuA2010 Structural geology and tectonic framework of the Shillong Plateau. Geological Survey of India Special Publication, V.71, pp. 45-63.

Sarkar S and Ray J., 2012 Karst geomorphology of the Shillong Plateau. Jour. of the Geological Society of India, 793289-297.

Seeber L, Armbruster J, and Quittmeyer., 1981, Seismicity and tectonics of the Shillong Plateau. Bulletin of the Seismological Society of America, V.712, pp. 389-400

Sharma S.P, Verma S. K and Kumar V., 2012, Aeromagnetic survey of the Shillong Plateau. Geophysical Research Letters, 398 L08305.

Spector A and Grant, F. S., 1970, Statistical models for interpreting aeromagnetic data. Geophysics, V.352, pp. 293-302.

Srivastava R.K and Sinha A.K., 2004 The early Cretaceous Sung Valley ultramafic–alkaline–carbonatite complex, Shillong Plateau, northeasternIndia Petrological and genetic significance. Mineralium Deposita, 80241–263.

Strong N, Goldstein S.L and Rosenfeld J. M., 2019, Geochemistry and tectonic history of the Shillong Plateau. Geological Society of America Bulletin, V. 1317, pp. 81333-1349.

Syiem S, Prasad S.B, and Gupta S., 2014, Gravity and magnetic analysis of the Shillong Plateau. Geophysical Journal International, V.1991, pp. 227-244.

Telford W.M, Geldart L.P, and Sheriff R.E 1990Applied Geophysics 2nd ed.. Cambridge University Press.

Tozer C, Ryu J, and Arnold E., 2019, Topographical data for geophysical research from Open Topography. Journal of Geophysical Research Solid Earth, V.1248, pp 6520–6532.

Tozer C, Ryu J and Arnold E., 2024, Update on Open Topography DEMs New datasets for global research. Geophysical Journal International, V.2332, pp. 745–762.