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Original Article

Investigating Geodynamic Processes and Regional Stress in Wadi Hagul, Egypt, Through Gravity and Seismicity Analysis

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Abstract

The tension and structural dynamics beneath Eastern Desert, Egypt namely Wadi Hagul, remain little comprehended despite intricate tectonic activity. This study aims to geodynamic processes in Wadi Hagul, Egypt, using gravity and seismic data to assess area stress levels. Seismicity data offers a thorough evaluation of stress levels in the research area, demonstrating a significant link between high-shear stress zones and the distribution of seismic activity. The northwestern region of the Gulf of Suez displays crustal tension in almost orthogonal orientations, while normal faulting predominates in the stress field. Our findings underscore notable regional disparities in stress regimes, signifying active faulting and deformation patterns. Gravity prospecting techniques provide significant insights, utilizing Bouguer anomaly maps derived from adjusted gravity data. Filtering algorithms identified local anomalies, and radial power spectrum integration determined the depths of shallow and deep sources, varying from 1 km to 3 km for gravity anomalies. Two-dimensional models based on Bouguer gravity data illustrated depths ranging from 0 m to -7000 m. Early basement maps showed that the Hagul region had different depths and tectonic activity. The study results highlight considerable tectonic activity and improve comprehension of geological dynamics, revealing structural patterns in many directions. The 2D models demonstrated a deepening of basement rocks to the north, while crustal thickness augmented to the south and diminished to the north. Our findings provide significant insights into the geodynamic processes and regional stress distribution in Wadi Hagul, with practical implications for seismic hazard assessment and resource exploration in tectonically active regions.

Keywords: Wadi Hagul; Seismicity; Stress; Bouguer Gravity; Geodynamic processes

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1. Introduction

Wadi Hagul is an intriguing geological formation characterized by active tectonic processes situated in Eastern Desert, Egypt. This region in Egypt possesses geological significance, providing distinctive study opportunities owing to its tectonic characteristics. Wadi Hagul in Egypt is a standout location due to its position at the boundary of significant tectonic zones, where the interaction of regional stresses and geodynamic processes is not well understood. Studying this area can help fill a crucial knowledge gap and provide insights into active deformation patterns and stress fields in similar geological contexts. This makes Wadi Hagul a unique and valuable research focus compared to other regions with similar tectonic activity. Previous research lacks comprehensive geodynamic evaluations of this region, highlighting the need to analyze gravity and seismic data to address this gap. Wadi Hagul, despite its geological importance, has not garnered substantial study interest, warranting a comprehensive investigation that includes seismic and other data (Seleem et al., 2011). We intend to clarify the geological processes influencing this region by integrating geophysical techniques, including gravity measurements and seismicity data. The combination of these datasets presents a unique opportunity to enhance our understanding of the structural constraints on stress distribution, fault dynamics, stress accumulation and release characterization, and seismic hazard potential assessment in Wadi Hagul (Morell et al., (2020). Figure 1 presents a locational map depicting fault lines and seismic activity in the Wadi Hagul region. Fault lines were extracted from the Egyptian Geological Survey.

Recent research indicates that from the Neogene to the Late Miocene, this region underwent multiple phases of migration. The initial formation of the Red Sea resulted from the northeastern movement of the Arabian Peninsula, subsequently advancing northward through the Gulf of Suez region, as documented by Hosny et al. (2013) and Bosworth et al. (2019). Approximately ten million years ago, the Nubian plate migrated northwest, resulting in the formation of the Gulf of Suez and the division of the Sinai sub-plate, thus establishing the present tectonic configuration, as detailed by Badawy et al. (2008). Geological and seismic studies indicate extensional movement along and near the Gulf of Suez (Abu El-Nader et al., 2018; Morsy et al., 2011; Salamon et al., 2003).

The elements of extension are fundamental mechanisms that characterize the Gulf of Suez region. The seismic activity in the Gulf of Suez is predominant in the southern part near the triple junction. On March 31, 1969, a Mw 6.6 earthquake on the Shadwan Islands resulted in damage, including many rock falls (Ambrasesy et al., 1994). Numerous geodetic and seismological investigations conducted in recent decades have comprehensively characterized the area's principal tectonic features. Earthquake fault plane solutions offered insights on the stress field within the examined region. The stress distribution is assessed primarily to identify stress variables utilizing data from the earthquake focal mechanism and the recurrent joint inversion for stress and fault orientations as presented by Vavrycˇuk et al. (2014).

The Cairo-Suez region is affected by three types of faults. The northeast and northwest faults are spread out, and the east-west faults often act as transfer zones, connecting the northwest and southeast faults at depth, as shown by Badawy et al. (2014) and Ali et al. (2019). Recent and paleo-earthquakes have created geological deformation patterns in the Wadi Hagul region and its vicinity, retaining sedimentary strata. The examination of several data types indicates that the Hagul fault zone predominantly governs the average depth of earthquakes in Wadi Hagul, which ranges from 1 to 35 km into the Earth's upper crust (Seleem et al., 2011). Figure 2 illustrates a structural geological map of the studied area. We have analyzed the current stress field in Wadi Hagul using an updated seismic focal solutions database spanning from 1951 to 2023. The fault plane solutions in Egypt demonstrate a geographical diversity of source processes that define the study area. The most efficacious way to elucidate stress relationships and tectonics is through the examination of earthquake occurrence data and geodetic information, as stress and strain fields are the fundamental drivers of earthquakes. Research suggests several migration phases from the Neogene to the late Miocene. The initial formation of the Red Sea resulted from the northeastern movement of the Arabian Peninsula, advancing northward along the Gulf of Suez (Bosworth, W., 2015). Seismic activity has migrated to the Jubal Island vicinity at the Gulf of Suez entrance, corresponding with the region's structural tendencies (Roberts H. H. and S. P. Murray., 1988).

The tectonic trend from WNW to NW shows active faulting, and most seismic activity happens on faults that run WNW-ESE to NW-SE and are under stress to extensional regimes (Abd El-Aal et al., 2019). Gaber, et al. (2022) employ gravity methods to establish structural trends and ascertain crustal thickness, and use regional-residual isolation approaches to outline tectonic processes influencing the basement surface and sedimentary layers. We assessed the depth of the basement using spectral analysis methods and two-dimensional profiles. To examine the subsurface structure and basement depths of the area, a comprehensive analysis using Bouguer gravity data is essential for prospective design. Through the study of Bouguer gravity and seismicity data, this work aims to help us better understand how the geodynamics of Wadi Hagul have changed over time by revealing subsurface structures and regional stress in areas that are actively tectonically active.

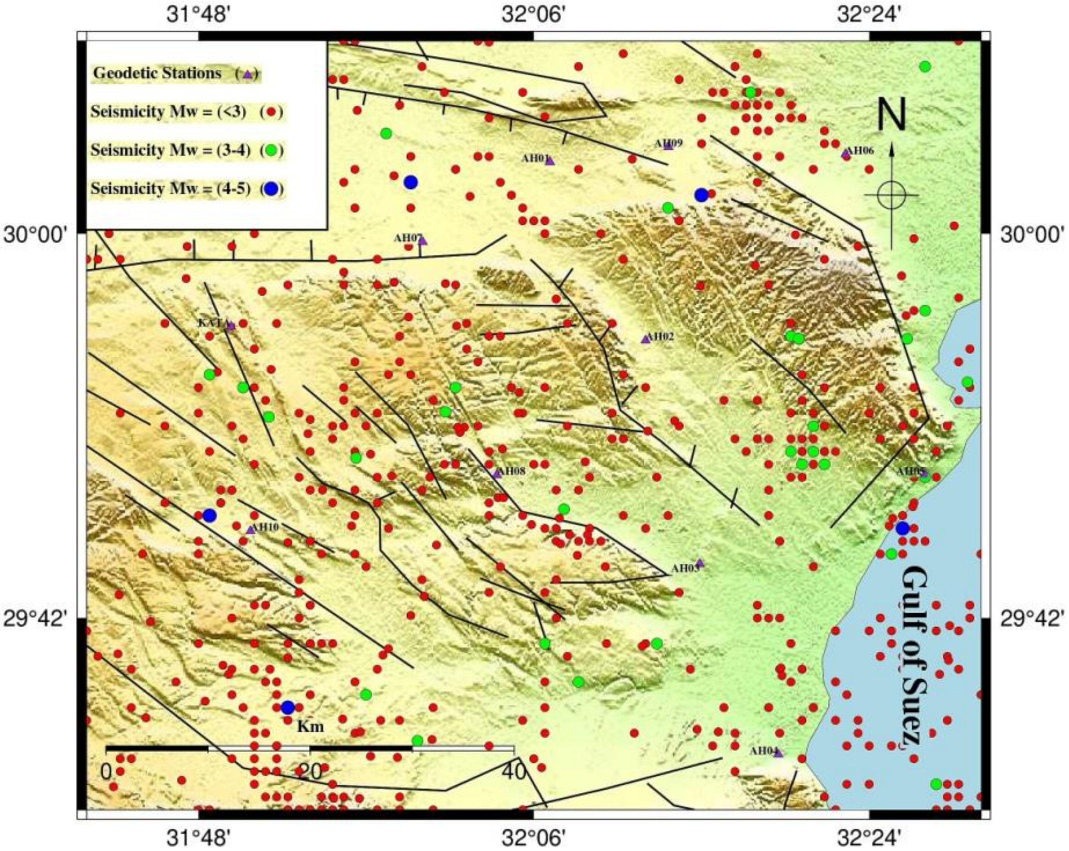

Fig. 1 Map depicting fault lines and seismic activity in the Wadi Hagul region, earthquake catalog from Egyptian National Seismological Network (ENSN) during the period from 1950 to 2022.

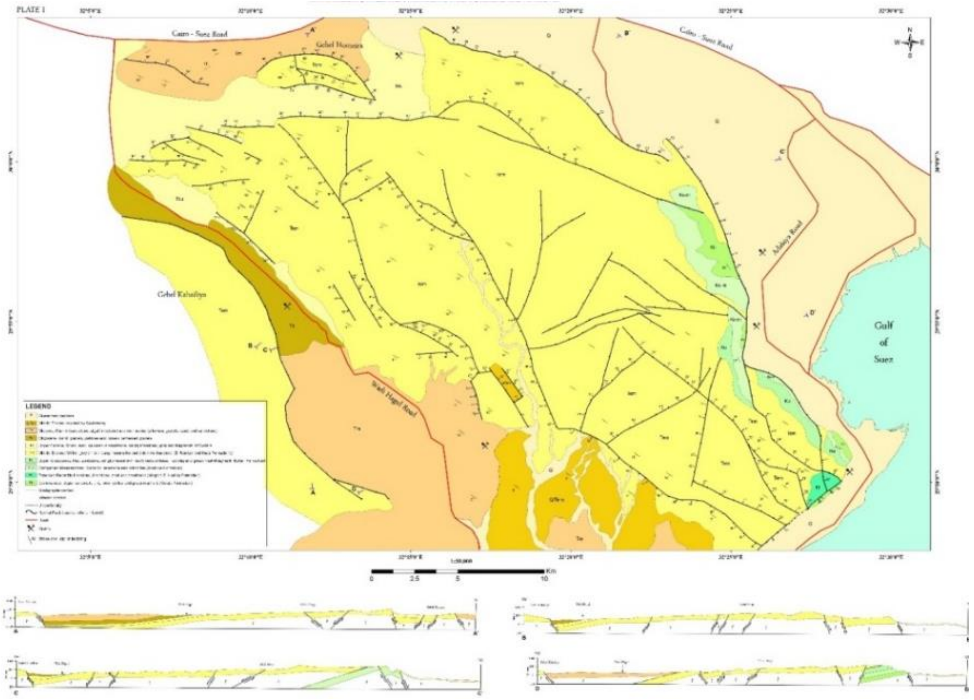

Fig. 2 Structure geological map around study area (after Moustafa, et al., 1997).

2. Materials and Methods

By utilizing data from publicly available catalogs and recent literature, we compile a database of focal mechanism solutions (FMSs) to enhance our understanding of established seismic and tectonic patterns, Abdelfattah, et al, (2024), Ali, S. M., and Badreldin, H. (2019), Badreldin, et al, (2018), we assessed the trend of tectonic displacement and visualized stress patterns across the research region. According to Martínez-Garzón et al. (2016), many of these techniques assume that the stress system is homogeneous within the selected temporal zone. Additionally, they rely on the assumption that the utilized focal mechanisms occur along existing faults with sufficient directional variation to effectively constrain the stress field. Since this approach works well in areas where there is limited knowledge of genuine tectonic faults, we applied it here. This technique, which employs a bootstrap replication procedure where each focal mechanism has an equal likelihood of being selected during resampling, allows for the identification of reliable regions of the optimal stress vector solution (Beaucé et al., 2022).

At least eight seismic stations are typically needed to accurately determine earthquake characteristics, with azimuthal gap less than 90% and error differences less than 20 for strike, dip, and rake (Hardback et al., 2002). We conducted stress tensor analysis after collecting and characterizing the available FPSs during the period from 1955 to 2022. The fault plane solution in Figure 3 corresponds to the seismic event that occurred on [23/01/2017], characterized by [magnitude: 3.9, depth: 6.46 Km, and location: Cairo Suez district], providing insights into the regional stress field and faulting mechanisms. In this region, normal faulting mechanism solutions were observed, resembling the mechanism of the Cairo–Suez district tectonic setting, Abdelfattah, et al, (2024), Ali, S. M., and Badreldin, H. (2019), Badreldin, et al, (2018). Figure 4 depicts (a) the frequency of earthquakes versus year and (b) the probability of exceedance versus magnitude. The seismic activity measurements were conducted using high-precision sensors capable of detecting ground motion with a high resolution. These specifications ensured accurate detection and characterization of seismic events critical for reliable focal mechanism analysis and stress distribution mapping.

The gravity method identifies fluctuations in the gravitational field resulting from alterations in subsurface density. This technique is crucial for geological investigations, including the mapping of near-surface voids, evaluation of metallic ore deposits, characterization of salt formations, and monitoring variations in fluid and gas content in volcanoes. Regional Earth characterization uses it to determine crustal features, identify potential resource exploration locations, and develop exploration models (W. J. Hinze et al., 2013).

The General Petroleum Company produced the Bouguer anomaly map in 1984 at a scale of 1:200,000. The station interval was 1000 m, the line spacing was 5000 m, and the contour interval was 1 mGal (EGPC, 1984) (Fig. 5). We used standard values of 0.3086 mGal/m and 2670 kg/m for the Free-Air and Bouguer adjustments, respectively. We performed accurate gravity measurements at multiple sites in Wadi Hagul. We observed seismic activity through a network of sensors. The data analysis encompassed gravity inversion and seismic wave interpretation. This method guarantees thorough understanding of geodynamic interactions.

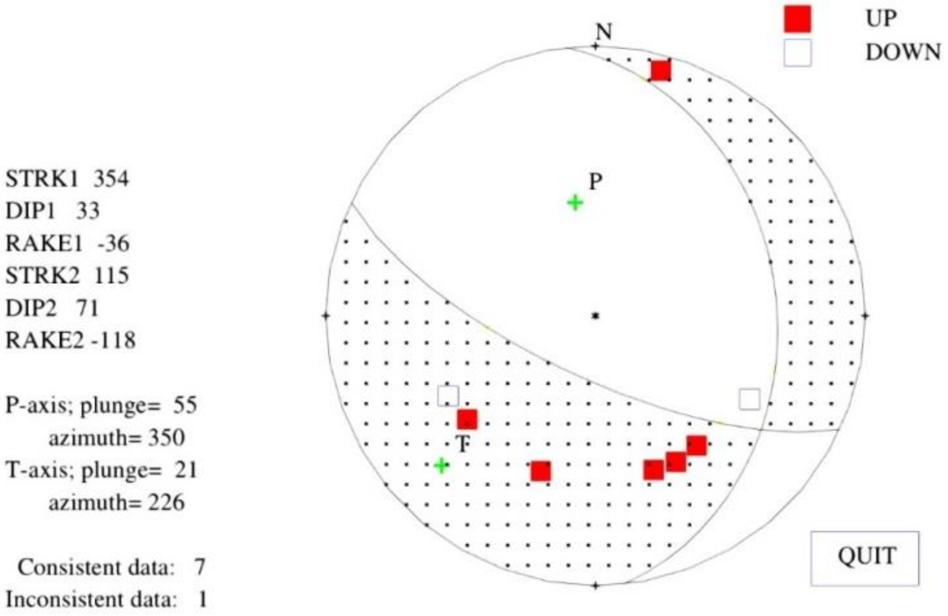

Fig. 3 Equal-area projections of the focal sphere for tremors under study in the southern hemisphere.

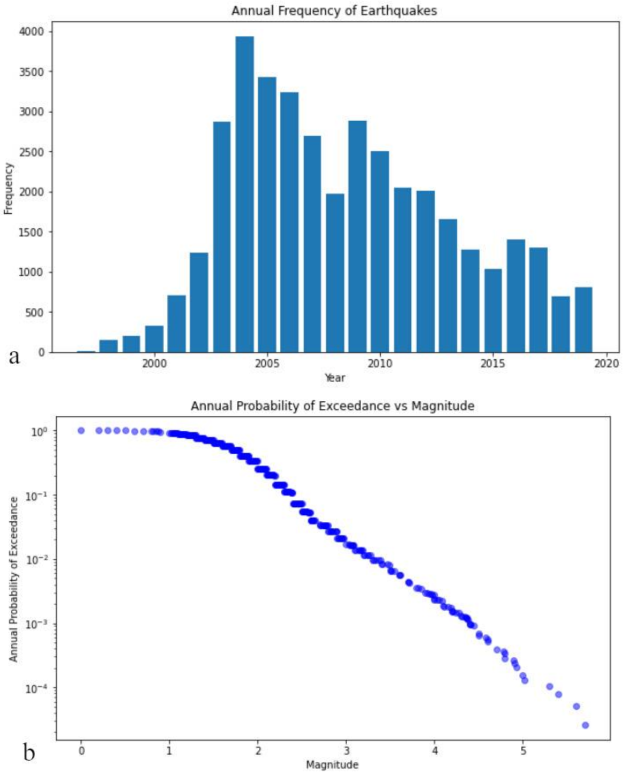

Fig. 4(a) Earthquake frequency by year and (b) probability of exceeding magnitude.

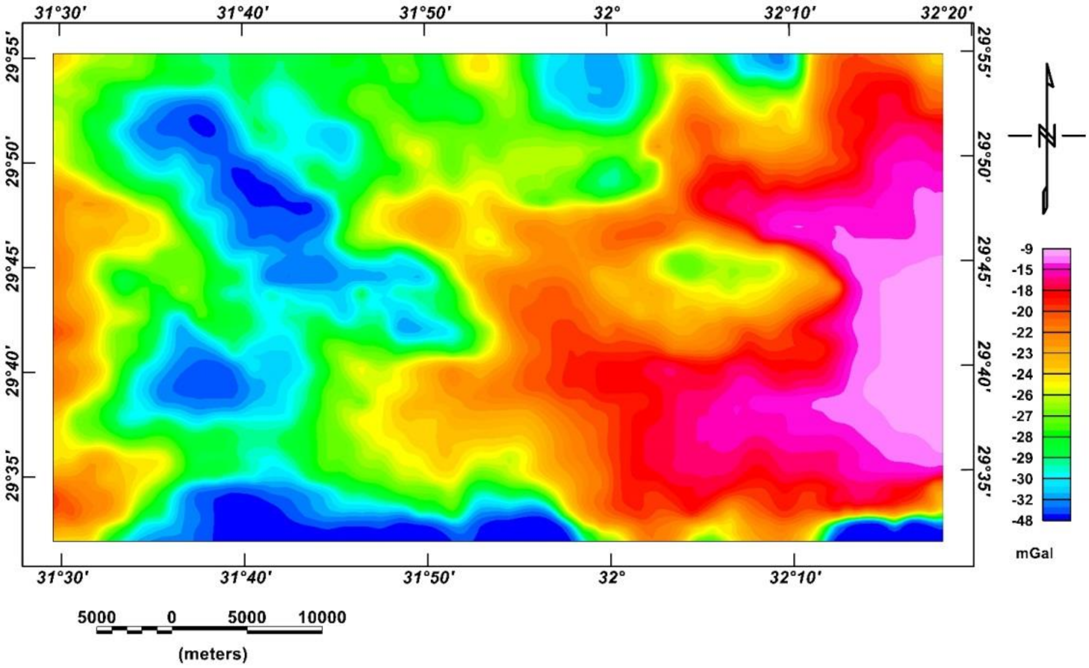

Fig.5 A Bouguer gravitational map of the study area.

3. Results and Discussions

Three principal abnormalities characterize the Bouguer anomaly map of the study region (Fig. 5). The western and northern anomalies travelling northeast have positive gravity anomaly values, reaching up to 48 mGal. Nonetheless, the SE anomaly exhibited a similar tendency, with negative gravity values reaching -9 mGal. The Bouguer map (Fig. 5) shows four negative areas that are either basins or down-faulted blocks. The amplitudes of these areas range from 9 to 48 mGal, and their orientation is from east to west, followed by northeast to southeast. On the other hand, we understand positive anomalies as elevated blocks surrounding these basins. Positive anomalies exhibit east-west, east-northeast, and west-northwest patterns. Linear anomalies indicative of faults have an east-west orientation. These anomalies are trending in NE, ENE, and NW directions. The regional-residual separation approach was used in the GM data to distinguish anomalies resulting from shallow geological origins from those arising from deeper sources. This procedure entails isolating the regional field from the observed field, yielding the residual field. Regional anomalies are often extensive and uniform due to their deeper and bigger formations, while residual anomalies have sharp gradients and elevated frequency owing to their superficial origins. Residual anomalies have significance in geophysical exploration.

Diverse techniques are used to identify residual components, with the analysis of the radial power spectrum of GM data serving as an appropriate and dependable tool for measuring the depths of various GM prospects characterized by differing densities or magnetic susceptibilities. Fig. 6 illustrates Bouguer maps for both the regional filter and the residual filter. Filtering techniques detected small anomalies, whereas radial power spectrum integration ascertained the depths of shallow and deep sources, ranging from 1 km to 3 km for gravity abnormalities. Fig. 7 illustrates the power spectrum and depth calculation for Bouguer gravity observations. The 3D Euler method for Bouguer fields was used to detect lineaments and faults in the focus area, in addition to ascertain their locations and depths. Fig. 8a presents the results of the study of the region's Bouguer observations using the Euler method. The Bouguer map enabled the exact localization of lineaments, geological contacts, dykes, faults, and sills (Fig. 8a) with a sensitivity index of 1. The Bouguer data indicates a depth range of 500 meters to a maximum of 3500 meters. The Rose chart (Fig. 8b) depicts the orientations of the structural elements in NE-SW and E-W directions. To evaluate the primary deformation characteristics and ascertain the risks in the study area, crustal deformation results were juxtaposed with seismological data from the same timeframe. The documented seismic activity indicated a correlation between present deformation and energy discharges linked to earthquakes (Etman, M. S et al., 2024). The seismic activity indicates the release of collected energy resulting from pressure accumulation between the Gulf of Suez and the Nile Valley, akin to the Dahshour earthquake of 1992. This study's events share similar main faulting processes, comprising a strike-slip component and a sub-vertical strike-slip component. The stress regime in this investigation is characterized by pure extensional forces accompanied by regular dip-slip faulting (Wael Hagag et al., 2016). The stress planes from the inversion were shown in a lower hemisphere projection, and the axis of the maximum perpendicular stress was ascertained by inverting the three principal stresses and the stress ratio.

Fig. 9 illustrates the findings of the stress study in this area. The Mohr circle diagram displays the stress inversion and result reliability. Blue crosses indicate the possible orientations of fault slips, specifically the single slip direction. Positioning these crosses around the largest Mohr circle could potentially render them unstable and link them to the real fault planes. The results showed that the stress field in this area changed between a normal faulting system and a strike-slip faulting mechanism, with an extra strike-slip component. We identified a characteristic faulting stress condition characterized by dual crustal extension around the Gulf of Suez, aligning with previous research. Ultimately, a close alignment of surface strain orientations and crustal stress in the studied area suggests that the same tectonic processes influence both trends. The gathered findings, together with seismological datasets used, enabled us to enhance our understanding of current stress within the research region. Figure 10 illustrates the present distribution of stress zones within the research region.

Four gravity models were constructed along profiles P1 to P4 using the GM-SYS tool in Geosoft Oasis Montaj to examine the composition and structures of the foundation. Two strata of sedimentary material were formed, with densities of 2.67 g/cc and 2.2 g/cc, and exhibited no sensitivity to magnetic fields. Gravity maps show profiles traversing areas with differing GM characteristics, aligned from south to north and westward using two reference wells (Fig. 11). Two-dimensional models were developed using the Geosoft mapping technology. The profiles revealed the presence of foundation rock south of Wadi Hagul, with sedimentary thickness augmenting toward the north. The profiles were modified to align observed and estimated data, with fitting errors ranging from 0.3 to 5 percent. The densities of different rocks were evaluated using Bouguer measurements. The sedimentary cover and basement rocks had average densities of 2.2 and 2.67 g/cm2, respectively, as established by comparisons with previous studies. All areas allocate profiles P1 to P4 (Fig. 11).

The detected anomaly along these profiles reveals a gravity field between -9 and -48 mGal, exclusively defined by negative anomalies. Two wells delineate the basement depths and sedimentary thickness along these profiles (Fig. 12). The modeled segment reveals a sedimentary cover depth ranging from 250 to 7000 meters. The modeled portions reached a depth of 7.5 km, covering an estimated distance of 100 km, which aligns with the foundation layer depth. Gravity data revealed distinct abnormalities associated with fault lines. Seismic measurements revealed heightened activity in several regions. The results indicate the presence of active tectonic processes. The findings demonstrate significant relationships between gravity and seismic activity. We observe similarities with other tectonically active areas. These findings enhance comprehension of regional geodynamics. Subsequent research may expand upon these basic discoveries.

Our research enhances the understanding of regional geodynamics in the Eastern Desert, building upon prior studies. It provides valuable insights for seismic risk management and urban planning in Wadi Hagul, guiding earthquake-resistant infrastructure design and resource exploration in active tectonic zones.

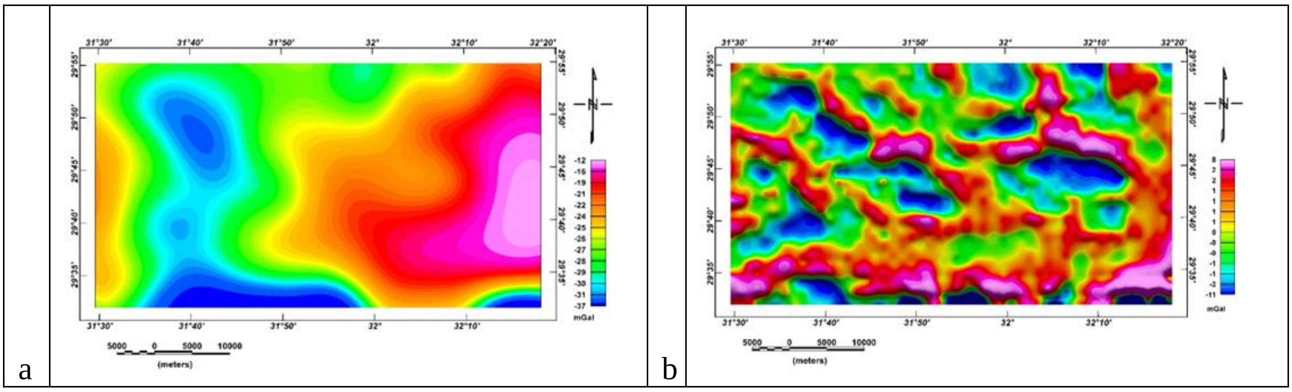

Fig.6 Bouguer anomaly maps use a) low-pass filters for regional analysis and b) high-pass filters for residual analysis, with a 0.023 cycles/km cut-off wave number.

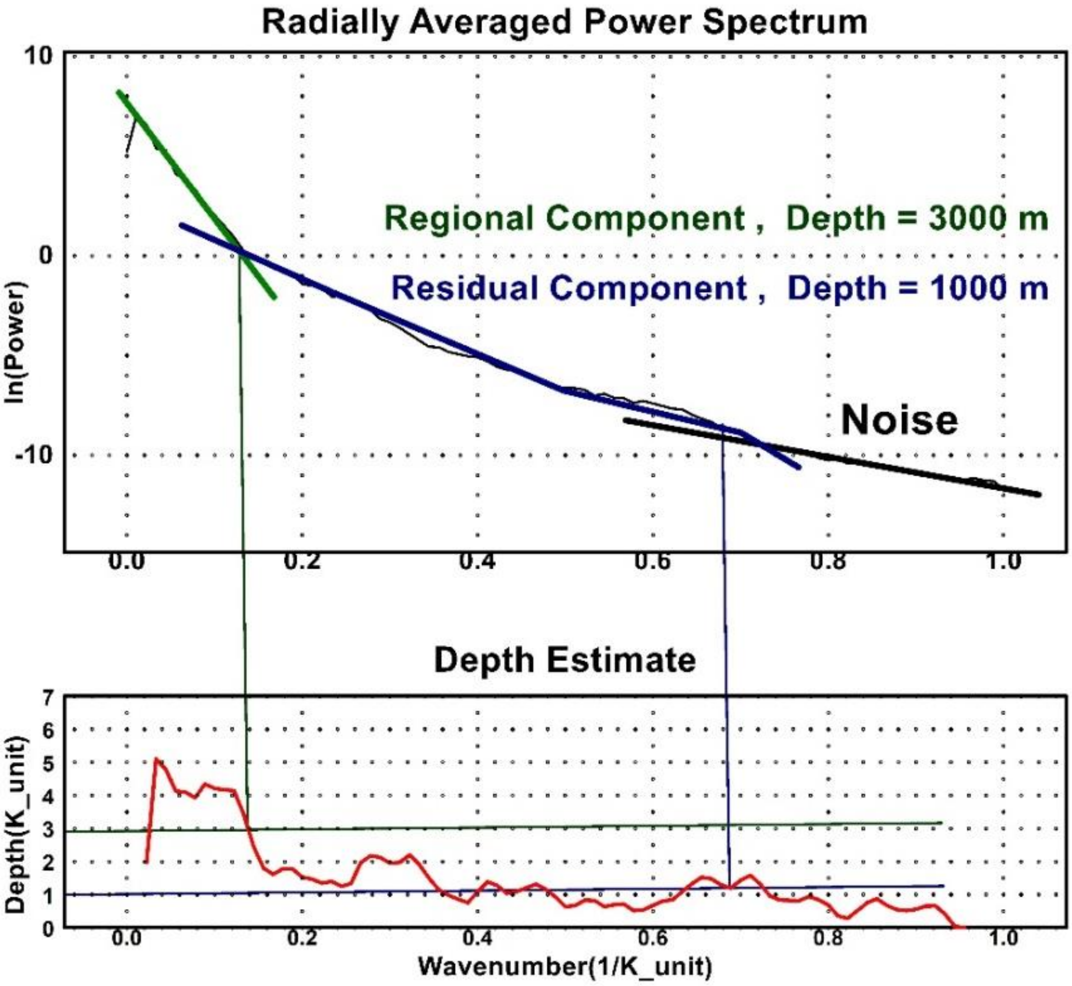

Fig.7 Radial power spectrum evaluation and depth estimation for Bouguer gravity measurements.

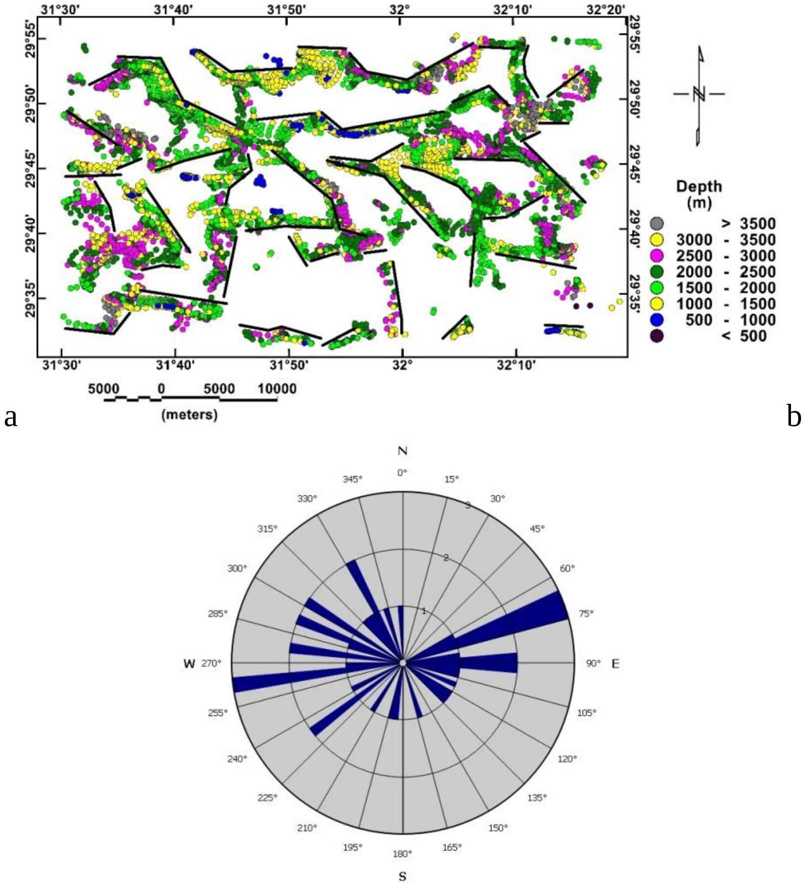

Fig.8 a) The Euler Deconvolution solutions map for SI (1) on the Bouguer anomalies pattern defines the position and depth of the faults. b) Rose chart is extracted from the Euler map.

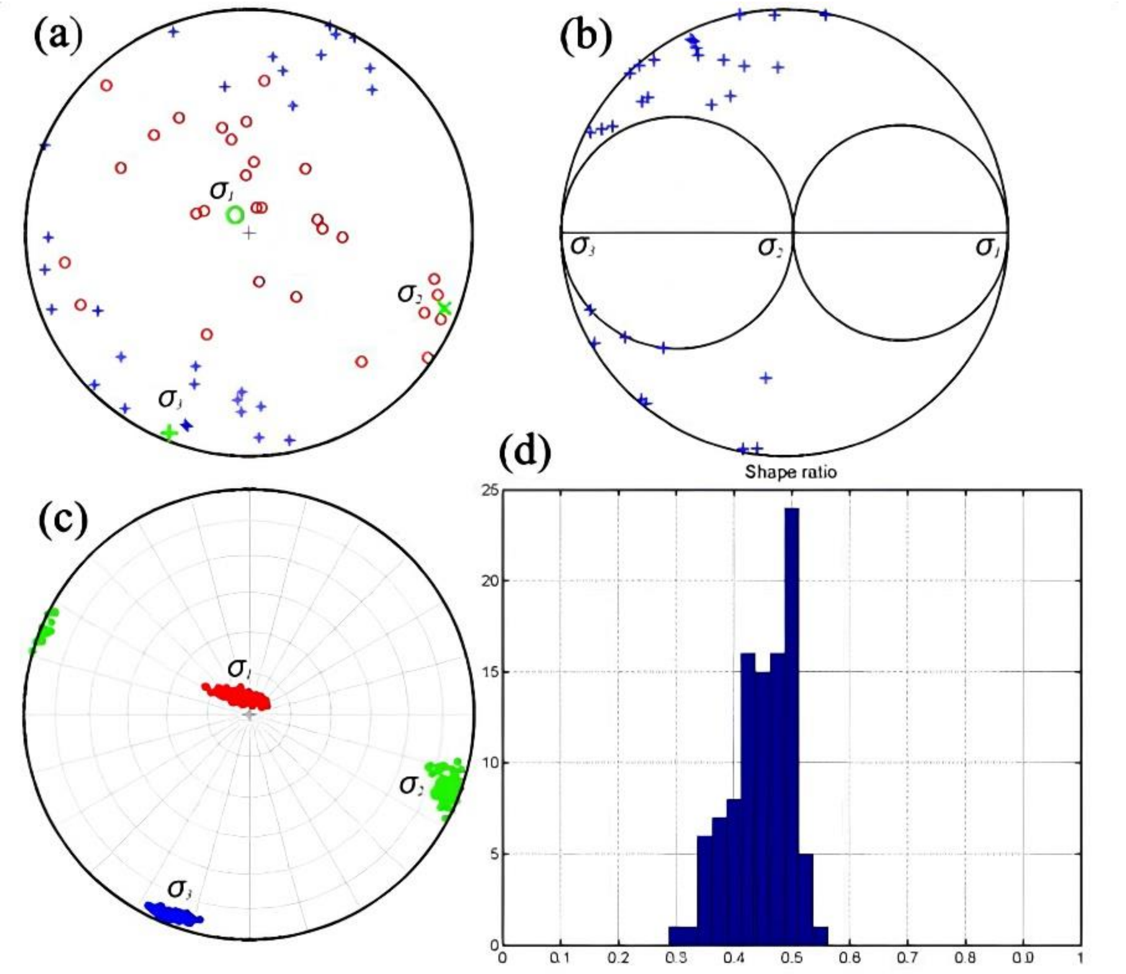

Fig.9 The stress analysis results include: a) focal sphere diagram with optimal stress axes; b) Mohr's circles with fault planes; c) plan of main stress directions; d) R desperation graph.

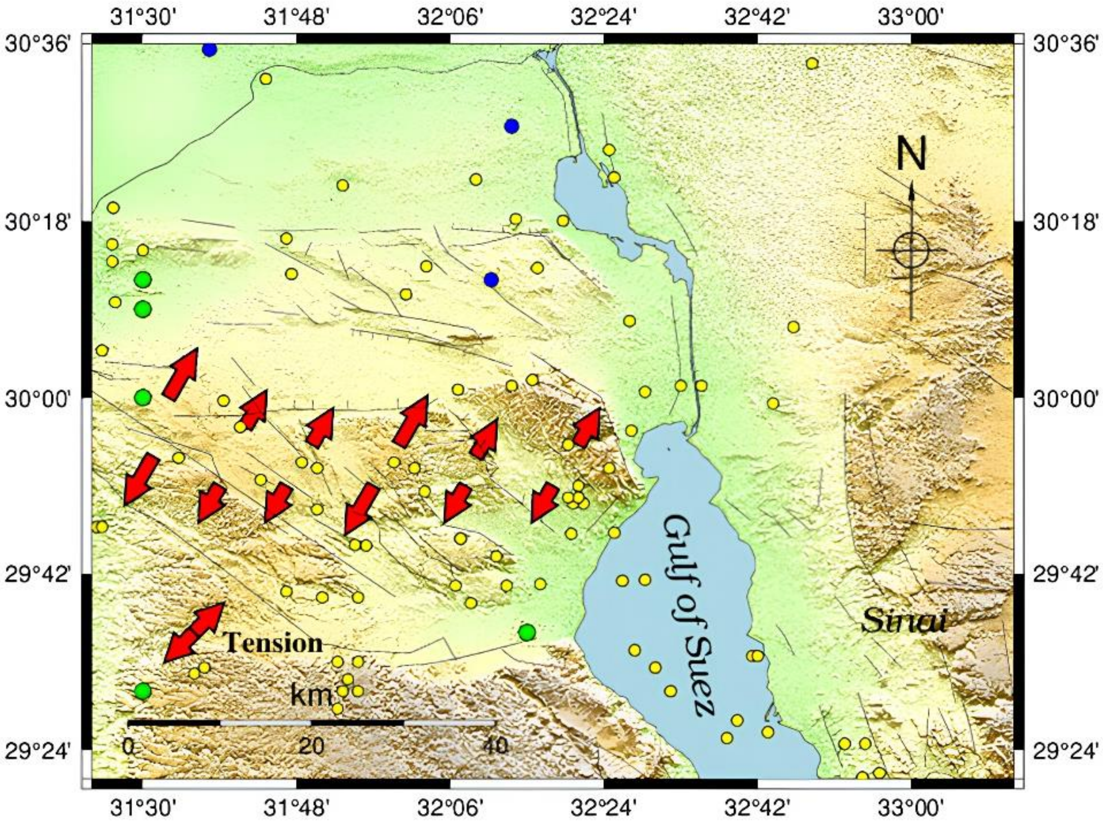

Fig. 10 Focus on the current stress zone distribution in the study area.

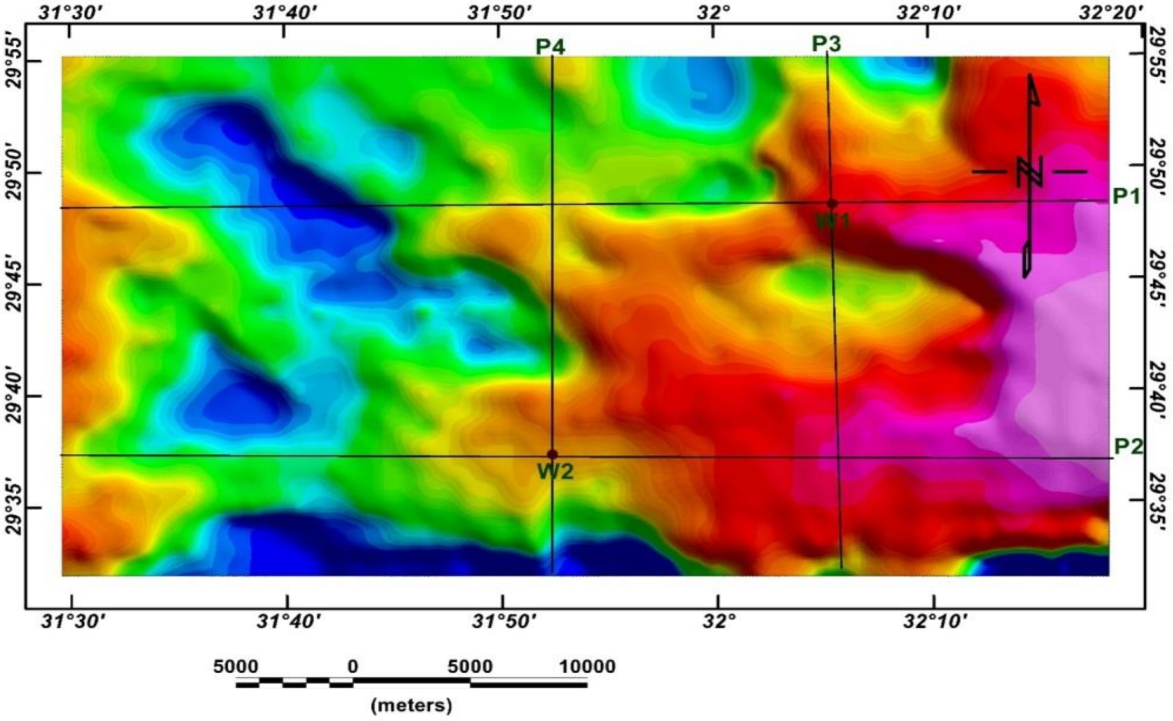

Fig. 11 The profiles for two-dimensional (2D) modeling of Bouguer gravity, along with the locations of the two well points.

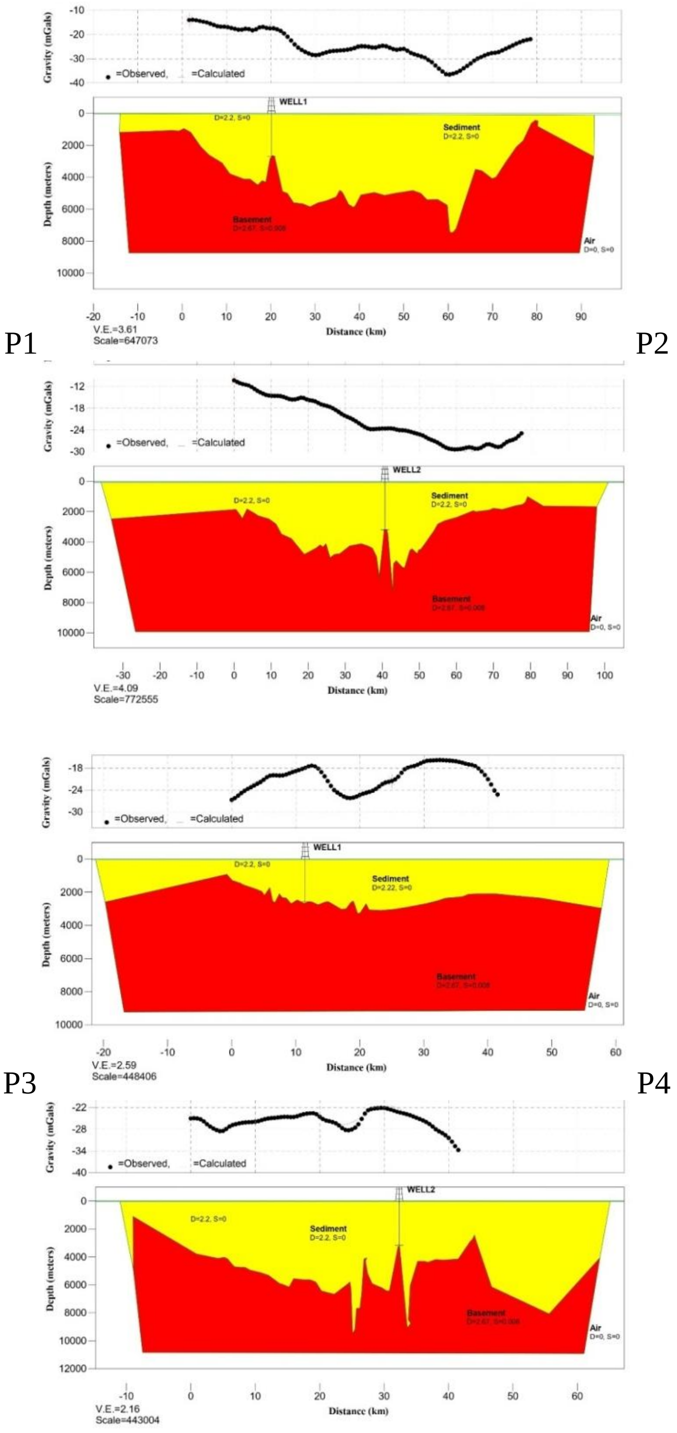

Fig. 12 Two-dimensional gravitational model of Wadi Hagul profiles (P1-P4) using reference depth points.

4. Conclusions

The principal axes of the strains indicate that extensional forces oriented in a northeast-southwest direction influence the region. The axes of compressive stresses derived from seismic fault plane solutions align with the principal axes of strain. To determine if the observable deformation is due to seismic activity, further repeated investigations with extended time intervals are necessary. Understanding the physical processes within the crust and predicting crustal activity requires monitoring temporal and spatial fluctuations in crustal stresses in this active tectonic zone. In the northwestern Gulf of Suez, the tension axes slightly rotate eastward while flowing northeast-southwest. The seismicity pattern in the area consists of active tectonic trends influenced by nearby active tectonic zones. Large-scale government projects, such as the development of new cities and urban expansion, may affect the stress regime in this sector, indicating their connection to the same principal tectonic stress zones. Tectonic activity shows significant uplift in the northwestern and central parts of the study area, as seen in the basement relief representation. Structural features in the region exhibit orientations in various directions, including NNW–SSE, E–W, and NE–SW. The southeastern section of the area detects a major fault. Crustal thickness decreases in the southeastern and northeastern parts of Hagul, while it increases toward the central area. This research uses 2D forward modeling, Euler deconvolution, and filtering methodologies to delineate structural components and depths within layers. A three-dimensional model of gravitational and magnetic data is crucial. This study offers new insights into the geodynamics of Wadi Hagul. The correlation between gravity and seismicity is vital for understanding tectonic dynamics. Further research will help clarify these complex mechanisms and provide valuable information for similar geological settings. Future research could expand upon this study by exploring the long-term evolution of geodynamic processes in Wadi Hagul, applying similar methodologies to other tectonically active regions worldwide to further refine seismic hazard assessments and regional stress models.

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Conflict of Interest: *The authors declare that they have no conflict of interests***.**

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Author Contributions

Mahmoud S. Etman conceptualized the study, conducted the data analysis, and composed the report. Salah Saleh and Abdel-Monem S. Mohamed participated in data collection, text composition, and material considerations. Sayed A. Mohamed contributed to data processing activities. Karrar O. Fergawy engaged in data analysis and conclusion formulation. All authors have examined and sanctioned the final version of the manuscript.

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