Frontiers in Scientific Research and Technology

Online ISSN: 2682-2970
Print ISSN: 2682-2962
http://fsrt.journals.ekb.eg

FSRT J 11 (2025) 45 - 50 10.21608/fsrt.2025.372752.1158

Structural Controls on Drainage Pattern: A Case Study from Northern Gebel Ataqa, Gulf of Suez Rift, Egypt

Ahmed Henaish[1], Moustafa Abdelhady[2], Fares Khedr[2], Sherif Kharbish[2,*]

[1] Department of Geology, Faculty of Science, Zagazig University, Zagazig 44519, Egypt

[2] Department of Geology, Faculty of Science, Suez University, Suez Governorate, El Salam City, 43518, Egypt

ARTICLE INFO

Article history:
Received 4 April 2025
Received in revised form 15 April 2025
Accepted 17 April 2025
Available online 20 April 2025

Keywords
Structural controls,
Drainage patterns,
Gebel Ataqa,
Gulf of Suez,
Rift basin,
Geomorphometry.

ABSTRACT

Drainage patterns are valuable indicators of geological structures and tectonic processes, especially in rift zones where structural elements play a significant role in shaping surface hydrology. This study investigates the structural controls on drainage patterns in northern Gebel Ataqa, situated along the western margin of the Gulf of Suez rift, Egypt. The region is characterized by extensional tectonics, with a complex network of normal faults, transfer zones, and fractures that influence drainage development. Using an integrated approach that combines field observations, remote sensing data, and geomorphometric analysis, the study identifies and classifies drainage patterns and their relationships with underlying structural features. Drainage density and stream order, reveal a strong correlation between fault orientations and drainage anomalies, including stream offsets and deflections. The findings demonstrate that the NW-SE and WNW-ESE fault systems act as primary controls, guiding drainage alignment and contributing to the development of dendritic, parallel, and trellis drainage patterns in different lithological and tectonic settings. This interplay between structural and geomorphological factors not only reflects the extensional tectonic regime of the Gulf of Suez but also provides insights into the region's tectonic evolution and surface processes. This study highlights the importance of integrating geological and geomorphometric techniques to understand the structural-geomorphic interplay in rift settings, offering a framework for similar investigations in other extensional regions. This research provides a documentation of structural-drainage relationships in northern Gebel Ataqa, integrating high-resolution satellite imagery with field-verified fault mapping. The study introduces conceptual models linking fault connectivity (simple, soft-, and hard-linked geometries) to drainage behavior, offering insights applicable to other extensional terrains.

1. Introduction

Drainage patterns serve as critical indicators of underlying geological structures and tectonic activity (e.g., Moustafa and Khalil, 2017). They provide insights into the interactions between lithological units, structural frameworks, and geomorphological processes. In tectonically active regions, such as rift zones, drainage development is often closely controlled by fault systems, fractures, and lithological variations (Henaish et al., 2022). The Gulf of Suez rift in Egypt is a classic example of an extensional tectonic setting where the interplay between tectonic activity and surface processes has shaped distinctive drainage patterns.

The Gulf of Suez rift is a prominent extensional basin formed during the early stages of the Red Sea rifting (e.g., Henaish et al., 2023; Youssef et al., 2023).

* Corresponding author at Suez University

E-mail addresses: sherif.kharbish@suezuni.edu.eg (Sherif Kharbish)

This rift system is part of a larger tectonic framework that evolved during the Oligocene-Miocene as a result of the divergence between the African and Arabian plates. The Gulf of Suez is characterized by a series of horst and graben structures bounded by normal faults, which define its distinctive asymmetrical geometry. These structural features control the distribution of sedimentary sequences, basin morphology, and surface drainage patterns.

Gebel Ataqa lies along the western margin of the Gulf of Suez and represents one of the key structural and geomorphological units in the region. The area is dominated by a thick sedimentary cover ranging from Paleozoic to Miocene age, with significant exposures of Jurassic and Cretaceous formations. These strata are frequently disrupted by faulting and folding associated with the extensional tectonics of the rift.

Northern Gebel Ataqa presents an ideal natural example for studying the influence of tectonic structures on drainage evolution. This region is characterized by complex fault systems, including normal faults and transfer zones, associated with the early stages of Gulf of Suez rifting (e.g., Henaish, 2023). These structural elements have significantly influenced the surface hydrology and landscape evolution of the area. Understanding these interactions not only contributes to regional geological knowledge but also has implications for hydrological studies, natural resource exploration, and erosion management.

Previous studies on the Gulf of Suez have largely focused on its tectonic evolution, stratigraphy, and hydrocarbon potential (e.g., Maqbool et al., 2014; Henaish et al., 2023; Henaish, 2023). However, fewer investigations have explored the structural controls on drainage systems (e.g., Henaish et al., 2022), particularly in northern Gebel Ataqa (Fig. 1). This gap provides an opportunity to link structural geology with geomorphological patterns and processes, shedding light on how drainage systems respond to tectonic forces in a rift setting.

The main objective of this study is to analyze the structural controls on drainage patterns in northern Gebel Ataqa. By integrating field observations, remote sensing data, and geomorphometric analysis, we aim to: (1) identify and classify the drainage patterns in the study area, (2) examine the structural features that influence these patterns, such as fault orientations, fracture networks, and lithological boundaries and (3) interpret the implications of these relationships for the tectonic and geomorphic evolution of the Gulf of Suez rift. This research not only enhances our understanding of the structural-geomorphic interplay in the Gulf of Suez but also provides a framework for similar studies in other extensional tectonic settings.

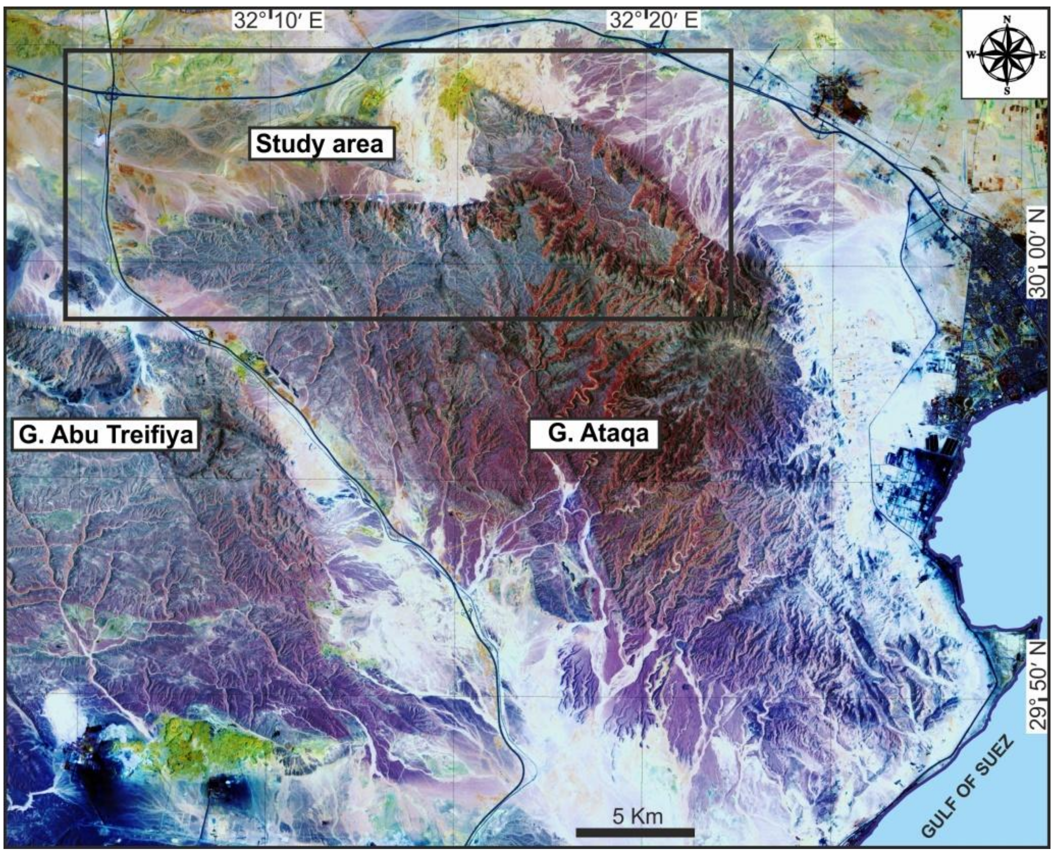

Figure 1: Landsat 9 OLI of the G. Ataqa area show the location of the present study area.

2. Stratigraphic Setting

The stratigraphy of northern Gebel Ataqa includes a variety of lithological units that contribute to the geomorphic and structural heterogeneity of the region (Fig. 2). The oldest unit is the Middle Eocene (Bartonian) Observatory Formation, approximately 80 m thick, containing chalky and dolomitic limestones, marl, and sandy marl beds. This is unconformably overlain by the Upper Eocene (Priabonian) Maadi Formation, 50-60 m thick, characterized by sandy limestone, fossiliferous marl, and shale. The Oligocene Gebel Ahmer Formation follows, a 30-35 m thick unit of reddish-brown sandstones, flint, chert, and quartzite, with Oligo-Miocene basalt flows indicating early Gulf of Suez rifting. The Miocene sediments, overlying older units unconformably, include the Lower and Middle Miocene Gharra Formation (48 m of dolostone, sandy limestone, and shale) and the Genefe Formation (62 m of algal and reefal limestones with marl), both rich in macrofossils. Upper Miocene rocks are represented by the Hagul Formation, a 20 m thick layer of yellow sand and gravel. Finally, Quaternary sediments of sand and gravel blanket the valley floors, reflecting the area’s complex tectonic and depositional history.

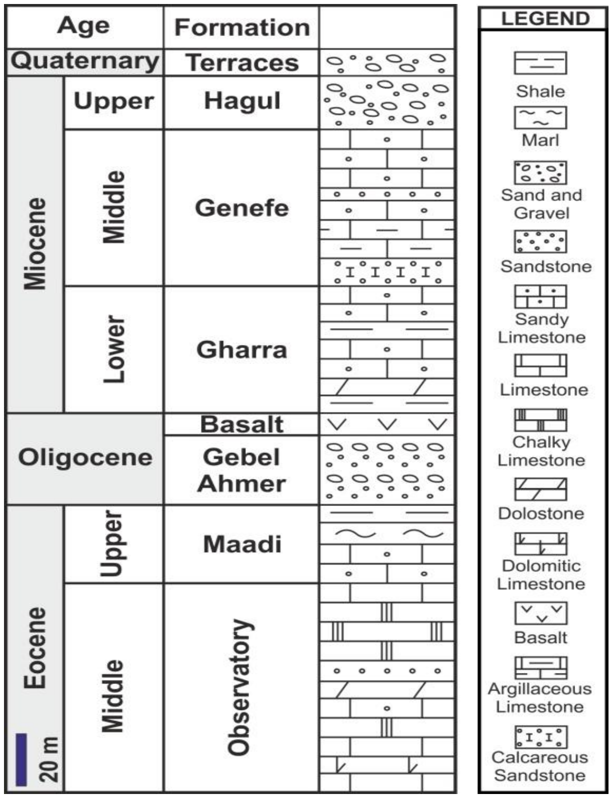

Figure 2: Composite stratigraphic column of north G. Ataqa (Compiled from El-Sorogy et al., 2017; present study).

3. Structural Setting

Field investigations in northern G. Ataqa reveal complex extensional structures, including step faults, horst-graben faulting, and fractures in Middle Eocene limestones near fault surfaces (Fig. 3). G. Ataqa, a horst block on the northeastern edge of the Gulf of Suez rift, is bounded by eight major faults with varying orientations and dip directions. In northern G. Ataqa, Middle and Upper Eocene rocks dominate, dissected by NNW-SSE normal faults and en echelon left-stepped faults forming the North Ataqa fault belt. G. El-Himeira, situated at the footslope of G. Ataqa, displays progressively younger rocks towards the northwest and includes NW-oriented rhombohedral and SE-oriented triangular horst blocks separated by a graben containing Upper Eocene and Oligocene rocks.

The structural analysis of the study area reveals a network of 45 fault segments categorized into three dominant trends (WNW-ESE, NW-SE, NNW-SSE) and two secondary trends (NNE-SSW, ENE-WSW), (Fig. 4). The study identifies soft-linkage transfer zones, including relay ramps in northern G. Ataqa and soft-linkage folds (single and multiple) in G. El-Himeira, as well as hard-linkage zones where transfer faults connect non-parallel segments, creating zigzag and rhombohedral geometries.

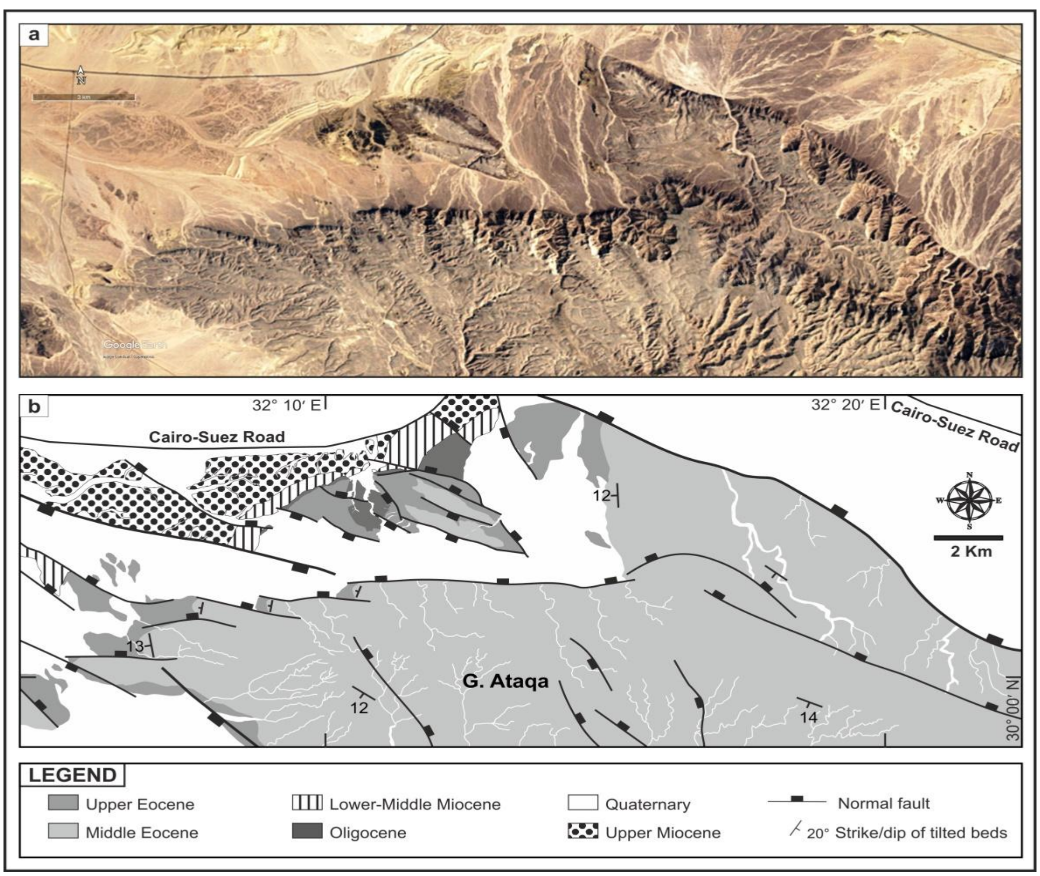

Figure 3: (a) Google Earth image of the northern G. Ataqa fault block. (b) Geological map of the study area (after Henaish et al., 2025).

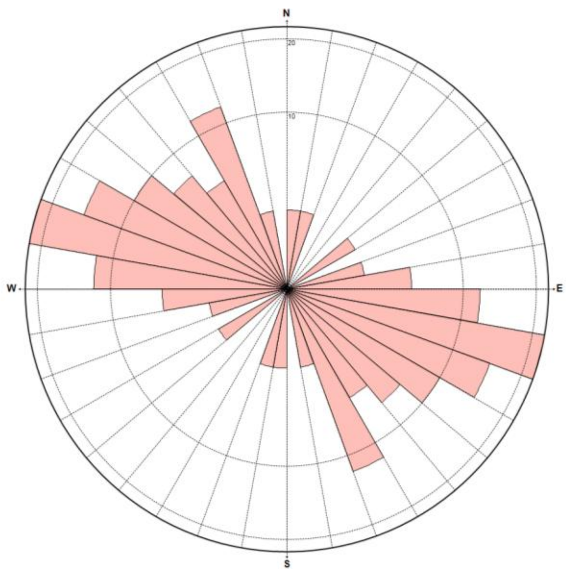

Figure 4: A rose diagram representing the main fault trends.

4. Remote Sensing Data

Active remote sensing technologies, particularly radar sensors, are highly effective for mapping drainage networks and identifying geological structures. One such example is the ALOS PALSAR data, which provides valuable elevation data. This data, produced by the Japanese Ministry of Economy, Trade, and Industry (METI) and Japan Aerospace Exploration Agency (JAXA), allows for near-global-scale elevation data collection, facilitating the creation of high-resolution digital topographic maps of the Earth's surface. For our research area, one ALOS PALSAR image with a spatial resolution of 12.5 meters was obtained from the US Geological Survey (USGS) website to cover the entire study region.

To support the research objectives, a range of GIS spatial analysis tools were employed. Initially, to map the drainage network, the clipped ALOS PALSAR image was processed with ArcGIS Hydro tools, following a sequence of operations: Fill Sink, Flow Direction, Accumulation, Stream Definition, Segmentation, and finally, Drainage Line Processing to generate the stream network. Additionally, the flow direction map was analyzed to explore the relationship between the stream network's flow paths and the area's slope and structural features. The image was also enhanced using the ArcGIS Hillshade tool, which produced relief-shaded images from two different azimuth angles (e.g., Abdullah et al., 2010). This shading technique helps highlight subtle surface variations that are crucial for identifying lithological discontinuities. These shaded images were combined into a single image using the Weighted Sum tool, allowing for the visual identification of structural features.

5. Results

In this study, pseudo-colored shaded relief images are used to highlight various linear and curvilinear features in the selected analysis sites, which may suggest the presence of fault structures (Fig. 5). Additionally, changes in terrain texture and pattern offer insights into the rock types, as seen in the northern G. Ataqa site. Regarding the identified drainage patterns, trellis, dendritic, and radial configurations were observed across the study sites. Two distinct drainage systems are evident: the older system, which includes higher-order branches (5th and 4th), and the more recent one, which features smaller-order branches.

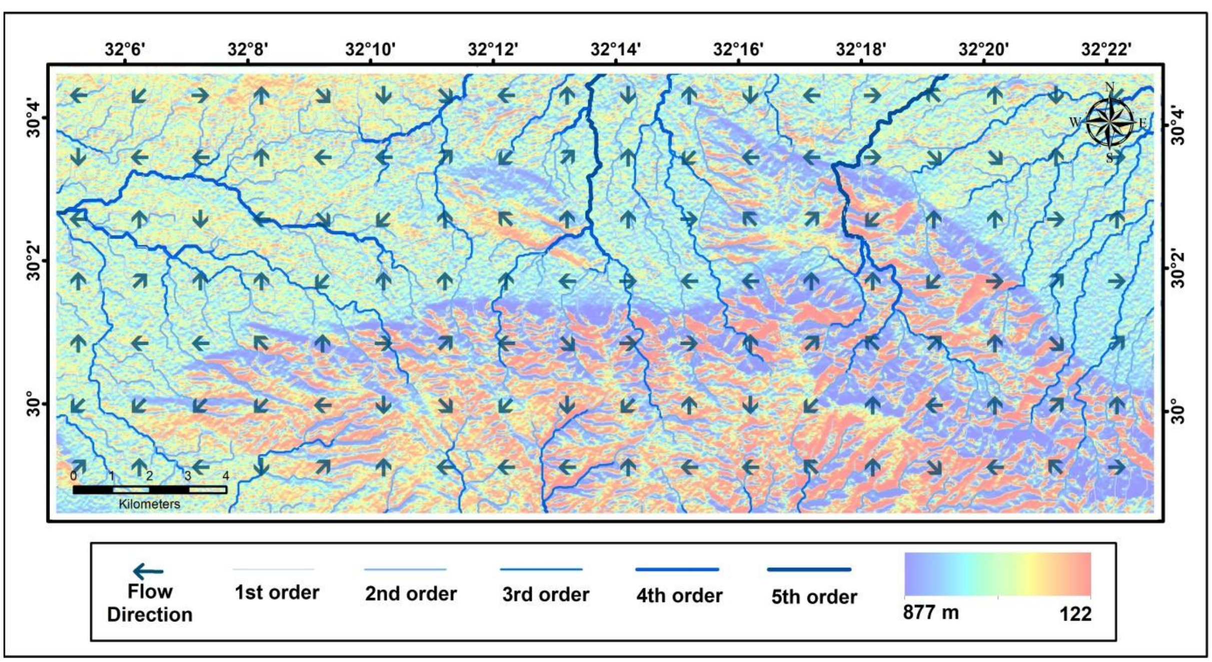

Figure 5: Extracted drainage network with the mapped structures overlaid on hill shaded ALOS PALSAR.

The flow direction of the drainage system in the study area is influenced by highly dynamic water flow, driven by variations in topography, lithological diversity, and structural complexity. These variations in flow directions will be discussed further in the following sections. Upon examining and correlating the drainage patterns along northern G. Ataqa, it becomes clear that they are primarily controlled by various structural geometries, predominantly faults, along with the dip direction of bedding planes. A comparison between field-mapped structures, supported by high-resolution Google Earth images, and drainage patterns extracted from DEMs revealed three distinct models of structural geometries influencing the drainage patterns. This comparison was based on the analysis of the geometry and attitude of mapped structures, represented as rose diagrams, alongside the extracted drainage (Figures 6 and 7).

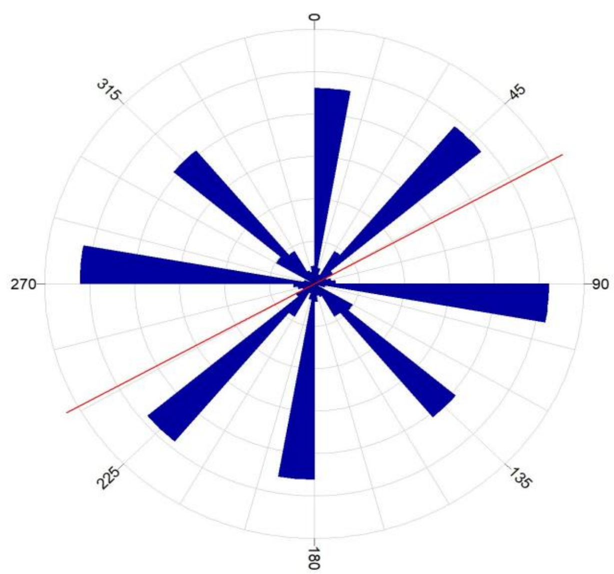

Figure 6: Trend analysis of high order streams.

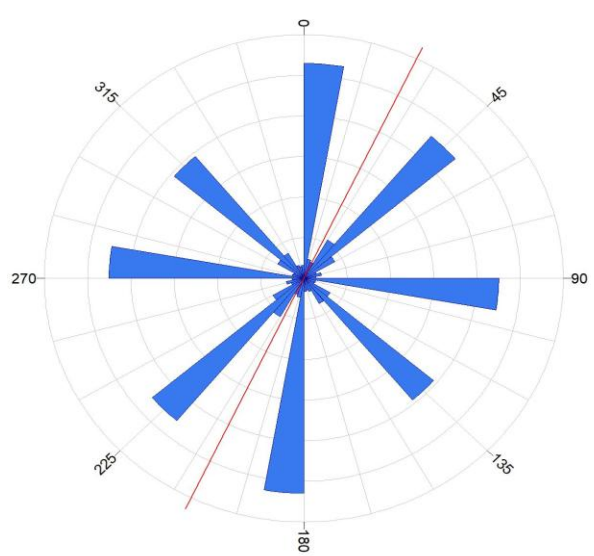

Figure 7: Trend analysis of low order streams.

These models arise from three main types of geological structures: simple fault planes, soft-linked faults, and hard-linked faults (Fig. 8). The first model is characterized by a single normal fault plane, which is linked to the dip direction of the bedding planes near the fault and the resultant cut-off angle between the fault and the bedding planes. In such cases, the drainage tends to flow either perpendicular or parallel to the fault plane. The second model involves drainage patterns related to soft-linked normal fault segments. These soft-linked faults are notably present at northern G. Ataqa, where a simple relay ramp forms between two overlapping WNW-oriented normal faults. The resulting drainage pattern is influenced by the dip direction of the relay ramp. Lastly, the third model pertains to hard-linked faults, which can be found at various locations, such as the eastern bounding fault of G. Ataqa. In these areas, drainage catchments appear at the footwall of the linked faults, while sedimentation accumulates at the hanging wall in the form of Quaternary deposits.

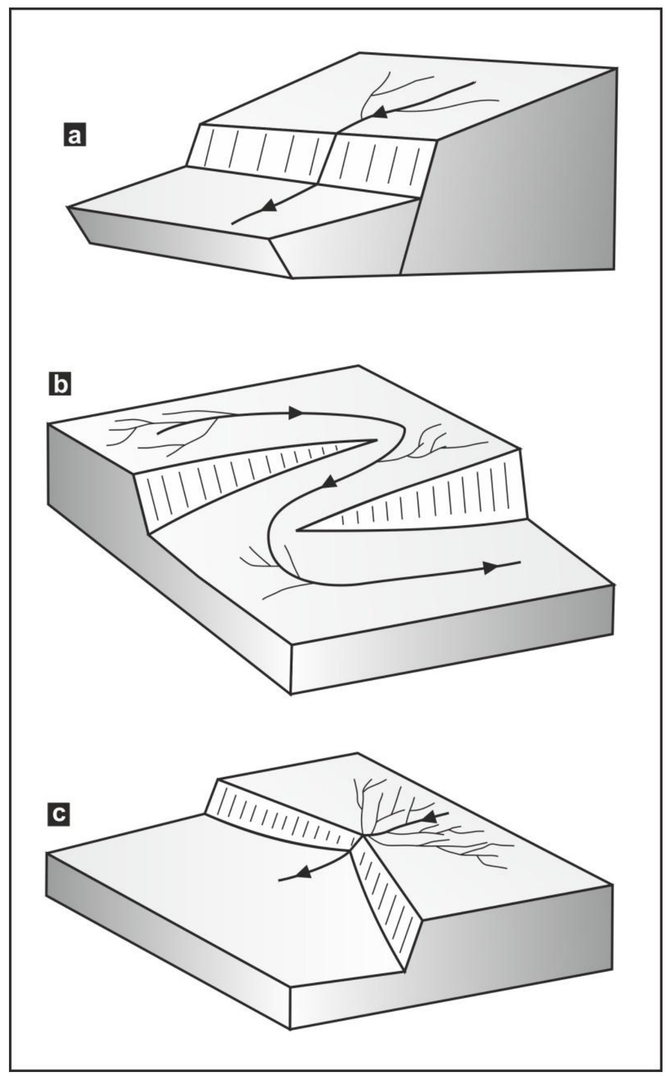

Figure 8: Proposed models of structural-controlled drainage at the present study.

6. Discussion

The relationship between tectonic structures and drainage patterns has been well documented in extensional settings worldwide. However, this study adds to the understanding by applying these concepts in the context of the Gulf of Suez rift, particularly in an understudied area like northern Gebel Ataqa. The three proposed drainage models (simple fault, soft-linked faults, and hard-linked faults) offer a conceptual framework for interpreting how fault architecture and kinematics influence surface hydrology.

The alignment of drainage with fault trends, especially the NW-SE and WNW-ESE systems, confirms the strong structural imprint on landscape evolution. The presence of soft-linked relay ramps and hard-linked rhombohedral fault blocks indicates that fault connectivity plays a crucial role in diverting, segmenting, or concentrating surface flow paths.

Moreover, the spatial correlation between drainage anomalies (deflections, offsets, and abrupt terminations) and fault intersections reflects the influence of both mechanical and lithological contrasts. The integration of these findings can inform future studies aiming to understand sediment transport, erosion rates, and even groundwater flow in structurally complex rift systems.

7. Conclusion

This study provides significant insights into the structural controls on drainage patterns in the northern Gebel Ataqa region, located along the western margin of the Gulf of Suez Rift. By combining field observations, remote sensing data, and GIS-based analysis, we have successfully identified and classified various drainage patterns, such as trellis, dendritic, and radial, and linked these patterns to the underlying structural and lithological controls. The analysis of fault orientations, fracture networks, and the dip directions of bedding planes revealed that drainage systems in this region are predominantly influenced by extensional tectonics, with fault systems playing a key role in shaping surface hydrology.

Three distinct models of structural geometries (simple fault planes, soft-linked faults, and hard-linked faults) were identified as the main factors influencing drainage development. The study shows that drainage tends to follow or intersect fault planes, with the most prominent flows occurring along the oldest and highest-order streams, which exhibit strong directional trends tied to fault structures. Furthermore, the study demonstrates the impact of soft- and hard-linked fault systems, where relay ramps and sedimentation patterns at fault footwalls significantly affect drainage catchments and hydrological pathways.

The findings underscore the importance of tectonic processes, particularly faulting, in the evolution of drainage systems in extensional tectonic settings. The integration of remote sensing data with field-based structural analysis provides a robust framework for understanding the geomorphological processes at work in rift zones, which can be applied to similar regions globally. This research contributes to the broader understanding of the relationship between tectonics and drainage patterns, offering valuable insights for hydrogeological studies, erosion management, and natural resource exploration in rift zones.

To further refine the understanding of drainage-structure interactions in the Gulf of Suez rift, future studies should consider the following: (1) Integrating geophysical data (e.g., seismic, resistivity) to resolve subsurface fault geometry and continuity; (2) Conducting hydrological modeling to quantify flow behavior across different structural domains and (3) Expanding similar studies to adjacent rift sectors to test the applicability of the conceptual drainage models presented here.

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