



Research Article

Quantitative Fault-System Architecture and Extensional Evolution. A case study of the Marib Sub-basin, Yemen

Saleh A. Ghareb^{1*}, M. Albaroot¹, Faisal A. Al-Oshari¹, Sourour Elgattoussi², Sadiq M. Al-Ahdal¹

¹Department of Applied Geology, University of Saba Region, Marib 00967, Yemen

²Laboratory of Georesources, Water Research and Technologies Centre (CERTe), Tunisia

*Corresponding author: salehgh7586@gmail.com
<https://doi.org/10.66973/geor.26.003>

Article info:

Received: 20 September 2026 /

Revised: 23 September 2026 /

Accepted: 25 September 2026 /

Published: 14 October 2026

Saleh A. Ghareb, M. Albaroot, Faisal A. Al-Oshari, Sourour Elgattoussi, Sadiq M. Al-Ahdal (2026).

Quantitative Fault-System Architecture and Extensional Evolution. A case study of the Marib Sub-basin, Yemen. Geology Reports, 1, 40-62. <https://doi.org/10.66973/geor.26.003>

Abstract: The objective of this study is to quantitatively analyze the fault-system architecture and extensional evolution of the Marib Sub-basin, Yemen. This was achieved by integrating subsurface 2D seismic reflection profiles and well-log correlations with direct surface geological mapping. A comprehensive dataset of 100 normal faults (21 exposed at the surface and 79 buried) was constructed to evaluate structural hierarchy and displacement partitioning. Results show that fault lengths range from 0.29 to 20.91 km, vertical throws from 10 to 3,804 m, horizontal heaves from 6 to 5,784 m, and net slips from 23 to 6,586 m. The frequency distributions exhibit a strong positive skew, indicating a mature extensional network where regional strain was predominantly absorbed by deeply rooted NW-SE master faults. Positive scaling trends on log-log graphs indicate progressive fault nucleation, lateral propagation, and ultimate linkage. We conclude that the basin evolved as an asymmetric, basement-controlled half-graben, strictly guided by inherited Precambrian fabrics. Unlike previous qualitative studies, this quantitative framework directly tracks displacement partitioning and structural inheritance, providing unprecedented additive knowledge and constraints for evaluating structural traps, fault seals, and reservoir compartmentalization for future hydrocarbon exploration in the Sab'atayn Basin.

Keywords: Marib Sub-basin; Sab'atayn Basin; fault-system architecture; fault scaling relationships; structural inheritance; extensional tectonics; basin evolution.

1 Introduction

Faults are fundamental geological structures created when tectonic stress exceeds the yield strength of the crust, leading to brittle failure. They are broadly classified into normal, reverse, and strike-slip faults

depending on the principal stress directions. Understanding how faults are created and how they control in-situ stress and well trajectories is critical for basin analysis and reservoir development, as demonstrated in recent geomechanical studies [27]. During the process of continental rifting, the primary

engines driving the stretching of the crust are normal faults. They carry the physical load of extension and directly create the accommodation space when the blocks separate [1-3]. Systems of faults typically arrange themselves into strict hierarchical orders as this extension happens. The majority of the strain is taken up by a few massive faults. The remaining deformation is handled by a swarm of smaller structures through nucleating, spreading, fragmenting, and linking [4]. The exact mechanical ways in which extensional basins grow and evolve can be pinned down by looking at the displacement partitioning and measuring the geometries of these faults [3, 4]. The Sab'atayn Basin is located down in the southern part of the Arabian Peninsula. This huge Mesozoic structure represents one of the most vital intracontinental rifts in Yemen. It preserves a critical archive of the Jurassic stretching events which radically reshaped the Arabian Plate [5-8]. It should be noted that the tearing of the region was not random. An inherited blueprint was left by the ancient Precambrian basement structures that already existed there, strongly guiding the deformation during the Mesozoic [9]. Consider the Marib Sub-basin situated on the western margin of the Sab'atayn. This specific depocenter is cut by an extremely complex network of faults. Structural

breaks can be seen right at the level of the outcrops, and they also extend deep into the buried stratigraphy. In the past, researchers who investigated this sub-basin mostly avoided the small details. They preferred to focus completely on regional plate tectonics, broad stratigraphy, or qualitative mapping alone. The fault geometry has not been quantified, the displacement partitioning has not been mathematically tracked, and the scaling laws have not been mapped out across the whole sub-basin in any previous study. A huge gap remains standing in the literature: is the geometry of the deeper, basement-controlled architecture accurately reflected by the shallow fault segments that are exposed at the surface?

In rift settings, determining how the strain is shared by the faults is essential. Everything from the overall shape of the basin to how it subsides and breaks apart structurally is dictated by the way the deep basement faults interact with the younger faults located in the sedimentary cover [1]. The existence of large subsurface structures here is known from seismic surveys, yet that represents only half of the picture.

To bridge this gap, the present study delivers the very first quantitative structural analysis of the Marib Sub-basin that is integrated at a basin-wide scale (Fig. 1).

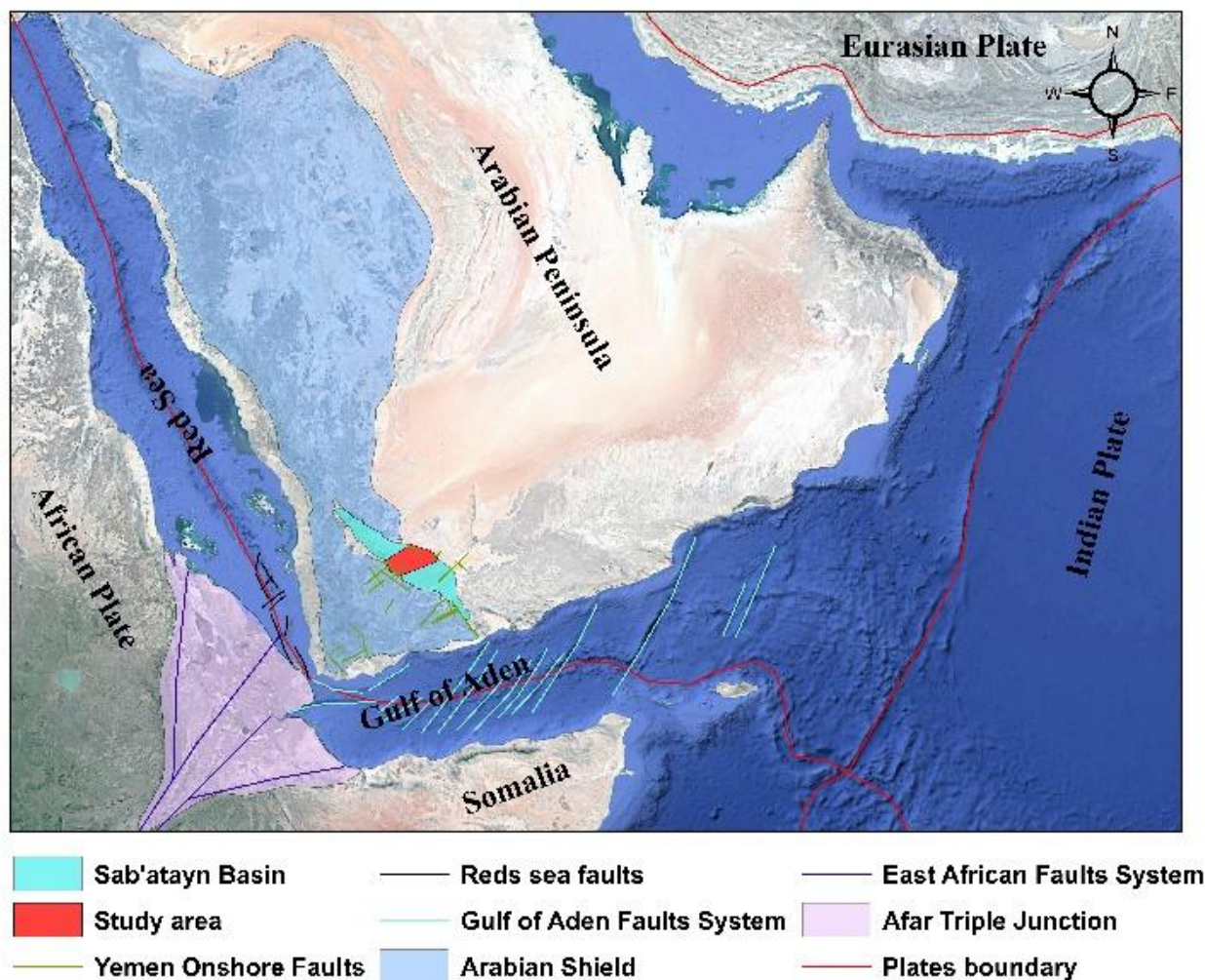


Figure 1. Location, geological setting, and tectonic framework of the Marib Sub-basin within the Sab'atayn Basin, Yemen. Regional location map showing the position of the Sab'atayn Basin within Yemen and the location of the Marib Sub-basin within the basin framework.

A massive dataset of structural elements was constructed by combining interpretations of deep seismic lines with field mapping of the surface geology. This was done to trace the tectonic evolution, crack the hierarchy of the faults, and establish the rules of scaling. Understanding the exact locations and mechanisms of displacement is not merely a theoretical exercise. Judging fault seals, tracing routes of fluid migration, finding structural traps, and figuring out how reservoirs are fragmented are all essential tasks for mapping petroleum systems, which require getting these numbers right. Four targets were set to be hit: (1) map the population's fault hierarchy; (2) determine the extent to which basin stretching was contributed to by surface faults

versus subsurface faults; (3) measure how fault length, heave, throw, and net slip are spread spatially; and (4) unpack the exact growth mechanisms of these faults using scaling relationships and statistics. The very first complete structural framework for the Marib Sub-basin is laid out by pulling all these quantitative and spatial measurements together. A much clearer picture is given by the results regarding fault growth, the mechanics of intracontinental rifting, and how strain is localized by ancient basement fabrics.

2. Geological setting

Positioned squarely within the western sector of the Sab'atayn Basin in central Yemen, the Marib Sub-

basin stands as a prominent Mesozoic intracontinental sedimentary depocenter. Continental extension during the Jurassic epoch drove its initial development. Gondwana fragmentation and early-stage rifting along the southern margin of the Arabian Plate governed these processes. An aborted continental rift system was thus formed. Syn-rift subsidence, extensive normal faulting, and deep-seated structural inheritance from ancient Precambrian basement fabrics characterize this domain.

A thick Jurassic-to-Cretaceous sedimentary succession is housed within the broader Sab'atayn Basin. These layers were accumulated within structurally controlled depocentres. Tectonic stretching associated with the breakup of Gondwana triggered this depositional phase. Extensional faulting, pre-existing basement discontinuities, and differential subsidence dictated the evolution of the basin. Subdivision into distinct structural domains was accomplished naturally. The Marib, Shabwah, and Jawf sectors emerged from this regional partitioning [10]. Unique fault architectures, varying sedimentary thicknesses, and distinct tectonic pathways are displayed by each sector.

Among these structural units, the Marib Sub-basin is recognized as a heavily developed depocenter. A complex network of faults is expressed directly at the surface and deep within the subsurface sedimentary succession. Deeper fault frameworks beneath the cover sequence are clearly revealed by seismic reflection data. Modern surface structures are exposed merely as the shallow manifestation of a much larger, basement-influenced deformation system. Normal faults, strike-slip structures, folding systems, joint sets, and dyke swarms have been documented by previous geological and geophysical investigations. Multiple phases of tectonic deformation and structural reactivation are recorded by these features. Inherited Precambrian basement architecture exerted strict control over the structural development of the sub-basin. Major basement terrane boundaries are located nearby. Transitions between the Abbas Terrane and the Al-Bayda Island

Arc establish this framework. Regional Precambrian structural trends tied to the Najd fault system exerted additional influence. Preferential zones for Jurassic extensional reactivation were provided by these inherited weaknesses. Fault orientations, segmentation patterns, and the spatial distribution of deformation across the entire basin were ultimately governed by these ancient fabrics.

Lithospheric stretching across southern Arabia during the Jurassic formed part of a broader regional event. Eastern Gondwana fragmentation and the widespread establishment of intracontinental rift systems throughout the Arabian-Nubian Shield drove this stretching. Widely accepted models of structural inheritance are supported by the reactivation of these Precambrian basement discontinuities. Pre-existing crustal anisotropies localized later extensional strain. The orientation, geometry, and ultimate evolution of the continental rift basin were dictated by this mechanical interaction [11, 12].

By combining seismic imaging, surface geological observations, and regional tectonic analyses, the Marib Sub-basin serves as an ideal natural laboratory. This framework enables the investigation of relationships among recognized structural models, fault growth dynamics, displacement partitioning, and strain localization within an intracontinental extensional setting. The exceptional preservation of both surface and subsurface fault networks provides a rare opportunity to directly integrate geological and geophysical observations into a comprehensive quantitative assessment of fault-system evolution.

3. Data and methods

3.1. Fault dataset

To minimize uncertainty and avoid relying on a single dataset, a comprehensive, multi-disciplinary approach was adopted. From the Marib Sub-basin, 100 distinct mapped faults were compiled into our structural dataset. In the subsurface, 79 of these structures were identified confidently. This was done by interpreting extensive two-dimensional seismic reflection profiles and supporting well-log correlations, which provided critical constraints on

deep structural geometries. Through rigorous geological field surveys, high-resolution Google Earth scans, published geological maps, and satellite imagery, the remaining 21 surface faults were located. A complete characterization of the basin-wide fault system was achieved by fusing these surface and subsurface records. The exposed counterpart could then be compared successfully against the buried structural framework. All fault traces were digitized and interpreted within ArcGIS 10.8 to process the data. Georeferencing every structural element and storing them inside a single, unified geospatial database was allowed by this step. After pulling the digitized traces directly from ArcGIS, the lengths of the faults were measured in CorelDRAW. The entire fault population was then divided into five specific hierarchical classes based on their geometric scale: minor, small, intermediate, major, and master faults. A log10-transformation was applied to the fault lengths before sorting them, because natural fault-length distributions skew heavily [13].

3.2. Geometric parameters

Four core geometric parameters were quantified for every mapped fault: net slip, heave, throw, and fault length. For overall fault size and structural maturity, fault length served as our primary metric, representing each structure's along-strike extent. The vertical component of displacement, known as throw values, was extracted directly from the seismic sections and structural maps [14]. The horizontal fault separation, or heave, was calculated from there. This was achieved by applying standard trigonometric functions to the measured throw and the known fault dip. Finally, by combining the throw and heave values, the total displacement vector (net slip) was determined. The geometric equations outlined by Ramsay and Huber [15] and Fossen [3] were used for this. All displacement math was run through automated Microsoft Excel spreadsheets to guarantee consistency across the dataset. Every single fault record had the mathematical equations

for heave and net-slip uniformly applied to it. The foundation needed to assess overall fault geometry, displacement partitioning, and hierarchical fault growth throughout the Marib Sub-basin was ultimately given to us by these quantitative metrics.

3.3. Statistical and spatial analysis

Rose-diagram generation, frequency distributions, logarithmic transformations, hierarchical classification, and descriptive statistics were heavily relied upon by our analytical approach. To compare fault length against the displacement metrics, log-log bivariate regressions were also run. All the statistical breakdowns, logarithmic regressions, frequency distributions, and histograms were handled by OriginPro 2024b. Meanwhile, the spatial analyses were run and the thematic maps were crafted using ArcGIS 10.8. The hierarchical distribution is completely dominated by the subsurface population, as shown by the data. In fact, solely in the subsurface dataset do every single master and major fault exist. The same applies to 37 out of the 38 intermediate faults. Conversely, a single intermediate fault, 6 small faults, and 14 minor faults make up the surface dataset, which mostly consists of smaller structures. Not even a single major or master fault is visible on the surface. Deformation spread out across dozens of subsidiary structures, which is proven by the fact that small and intermediate faults together make up 64% of our total dataset. However, the vast majority of the cumulative displacement was accommodated by the handful of master and major faults. The structural architecture is heavily dominated by them as a result. Continuous, basin-scale structural corridors are formed by the largest faults, which cluster tightly in the north-central and central zones of the basin when looking at the spatial distribution. Although scattered throughout the basin, intermediate faults gather thickly in the northeastern and southeastern corners. Short, discontinuous segments distributed widely along the basin margins describe the minor and small faults (Table 1).

Table 1. Hierarchical classification and distribution of surface and sub-surface faults in the Marib Sub-basin.

Fault class	Total	Sub-surface	Surface
Master	2	2	0
Major	20	20	0
Intermediate	38	37	1
Small	26	20	6
Minor	14	0	14
Total	100	79	21

A sharp hierarchical structure is displayed by this fault population in short. A few massive, basin-scale structures exist alongside numerous small faults. The actual structural framework of the Marib Sub-basin is held by the buried fault system. Just a tiny fraction of the overall network is represented by the exposed surface faults. Finally, to better understand fault growth and displacement scaling, logarithmic bivariate regression analyses linking fault length with net slip, heave, and throw were performed. Coefficients of determination (R^2) were used to evaluate the strength of these scaling relationships. To evaluate fault segmentation, linkage, and structural maturity, the resulting scatter patterns were interpreted.

4. Results and Discussion

4.1. Fault orientation

Exactly 100 mapped faults are contained within the integrated dataset. Subsurface structures account for

79 of these. The surface exposes the remaining 21. Lengths for these faults fluctuate between 0.29 and 20.91 km. Vertical throws span 10 to 3,804 m. Heaves stretch from 6 to 5,784 m. Net slips are pushed from 23 up to 6,586 m. A heavily hierarchical organization is exhibited by the population. Intermediate and small faults dominate this network. The vast bulk of basin-scale deformation is absorbed by a limited number of master and major faults.

A well-defined structural grain is revealed by the orientation analysis. NW-SE striking faults dominate the rose diagrams (Fig. 2). This specific orientation acts as the principal structural fabric across both datasets. The highest frequency peaks on the rose diagrams express this dominant trend. A consistent basin-wide structural alignment is explicitly demonstrated.

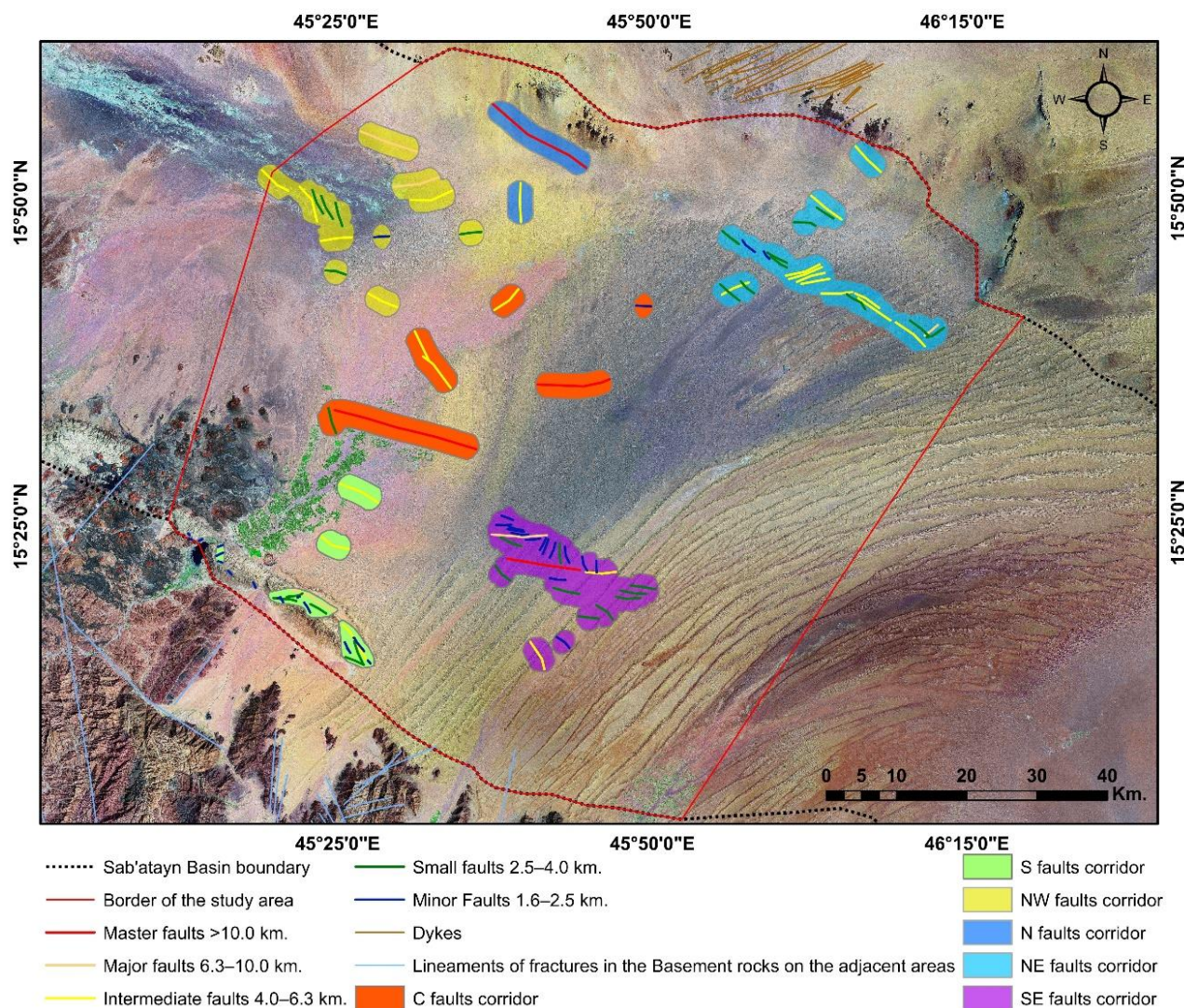


Figure 2. Rose diagrams showing the orientation patterns of the surface and sub-surface fault systems in the Marib Sub-basin. (A) Rose diagram of sub-surface fault strikes. Fault strikes are predominantly NW–SE, indicating extension approximately perpendicular to the fault trend in a NE–SW direction.

Subordinate NE–SW-oriented faults exist. These are seen mostly deep underground. Their frequency sits far below the NW–SE trend. E–W and N–S striking sets are developed locally. These make up a tiny fraction of the total faults.

Orientation patterns are mirrored closely between the surface and subsurface. Longer, continuous NW–SE structures are concentrated heavily underground. Shorter, disconnected segments characterize the surface faults. The dominant structural orientation is preserved regardless. The deep structural geometry is perfectly reflected by the exposed shallow networks.

The entire Marib Sub-basin is crossed by the NW–SE trend. This forms the main basin-scale system. Secondary structures tied to local complexities dictate the placement of the NE–SW, E–W, and N–S sets.

NW–SE striking faults dominate the rose diagrams. Subordinate sets fill in the gaps. The architecture of the basin was controlled outright by NW–SE extensional tearing.

4.2. Fault length

Fault lengths across the Marib Sub-basin exhibit massive variability, ranging from 0.29 to 20.91 km. These dimensions reflect a structurally diverse

population comprising both short subsidiary fractures and large basin-scale faults. The analyzed dataset consists of 100 faults, with 79 identified through subsurface records and 21 mapped at the surface.

Short to intermediate structures completely dominate the frequency distribution (Fig. 3).

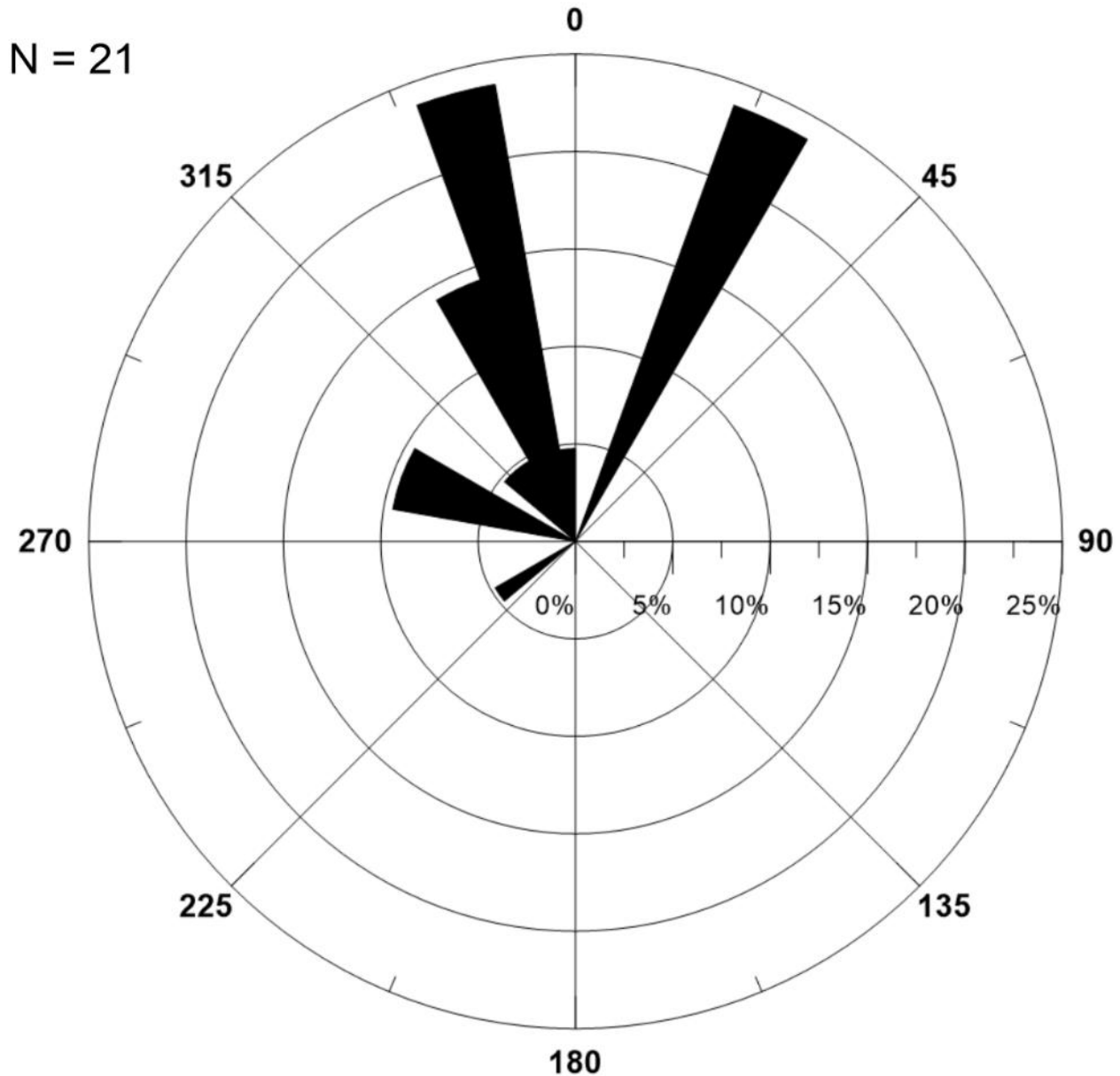


Figure 3. Frequency distributions of the principal fault geometric parameters in the Marib Sub-basin. (A) Fault length, (B) throw, (C) heave, and (D) net slip. The distributions are positively skewed, with a predominance of short and low-displacement faults and a limited number of long and high-displacement faults, reflecting the hierarchical organization of the fault population and the dominance of small- to intermediate-scale structures within the sub-basin.

Five hierarchical groups are formed based on length. Two master faults exceed 15 km. Twenty major faults fall between 7 and 15 km. Thirty-eight intermediate faults measure 3 to 7 km. Twenty-six small faults sit between 1 and 3 km. Fourteen minor

faults fail to reach 1 km. The largest slice of the dataset is claimed by intermediate faults (38%). Small faults take 26%. Major structures claim 20%. Minor faults grab 14%. Master faults represent a tiny 2%.

The absolute longest faults are trapped strictly underground. These form continuous structures stretching beyond 15 km. Short, broken segments characterize the surface population. Zero master or

major faults are exposed above ground. The central and north-central basin sectors host the longest structures (Fig. 4). Shorter faults are scattered widely across the margins.

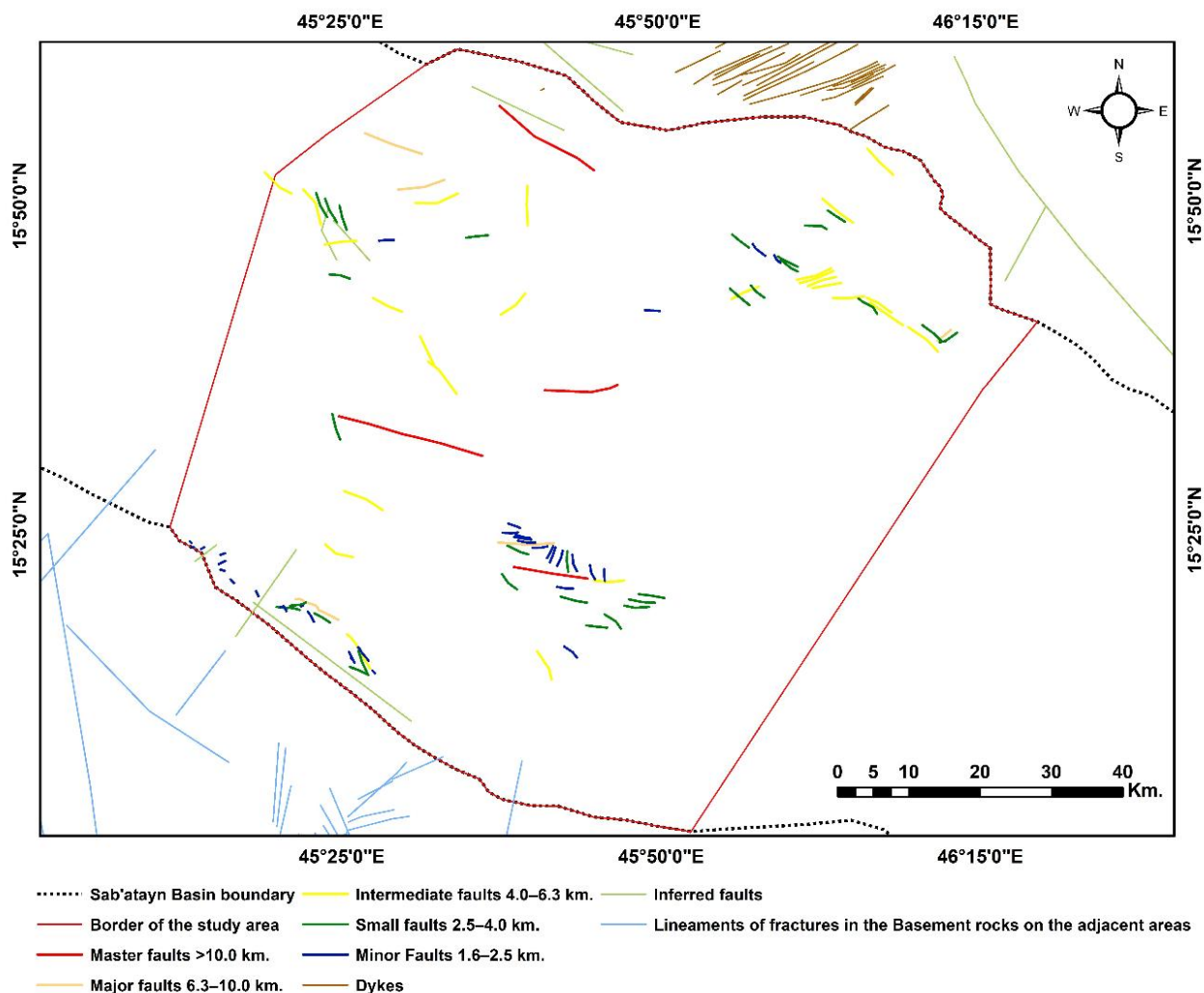


Figure 4. Spatial distribution of fault length in the Marib Sub-basin. Fault length is unevenly distributed across the study area and is concentrated within a limited number of major structural corridors dominated by master and major sub-surface faults. These long faults define the principal basin-scale structural grain, whereas shorter faults occur more diffusely as subordinate intermediate, small, and minor fault segments.

A positively skewed distribution is displayed by the histogram (Fig. 8). Short faults appear with incredibly high frequency. A steep drop-off occurs as length increases. The structural framework is built by a few massive faults. The remaining population is flooded with short structures. Logarithmic separation of the length population was used to select these thresholds. Natural geometric breaks dictated these boundaries. Arbitrary intervals were avoided.

4.3. Fault throw

The vertical component of displacement is represented by fault throw. The tectonic accommodation and structural growth within the Marib Sub-basin are quantified by this metric (Fossen, 2016). A broad spectrum is shown by the measured throw values. The hierarchical nature of the system is reflected here. Deformation was partitioned

progressively. Large basin-bounding faults handed strain down to smaller subsidiary structures.

The basin architecture is predominantly defined by moderate- to high-displacement normal faults, with the most extreme throws localized along the principal NW-SE basin-bounding structures. These major extensional systems controlled the formation and subsidence of the half-graben, whereas the smaller

intra-basinal faults record much lower throws, functioning primarily as secondary accommodation features during progressive stretching. These functioned merely as secondary accommodation features born during progressive stretching.

Four characteristic displacement domains are defined by the measured values, with throws ranging from 10 to 3,804 m (Fig. 5). [Table 2]

Table 2. Fault classification and structural significance based on throw displacement values.

Fault hierarchy	Throw range	Structural significance
Master faults	1000–3800 m	Principal basement-involved faults controlling basin architecture and major subsidence
Major faults	316–1000 m	Significant syn-rift faults accommodating regional extension
Intermediate faults	100–316 m	Secondary faults linking and segmenting major structures
Small faults	<100 m	Localized deformation structures and late-stage accommodation faults

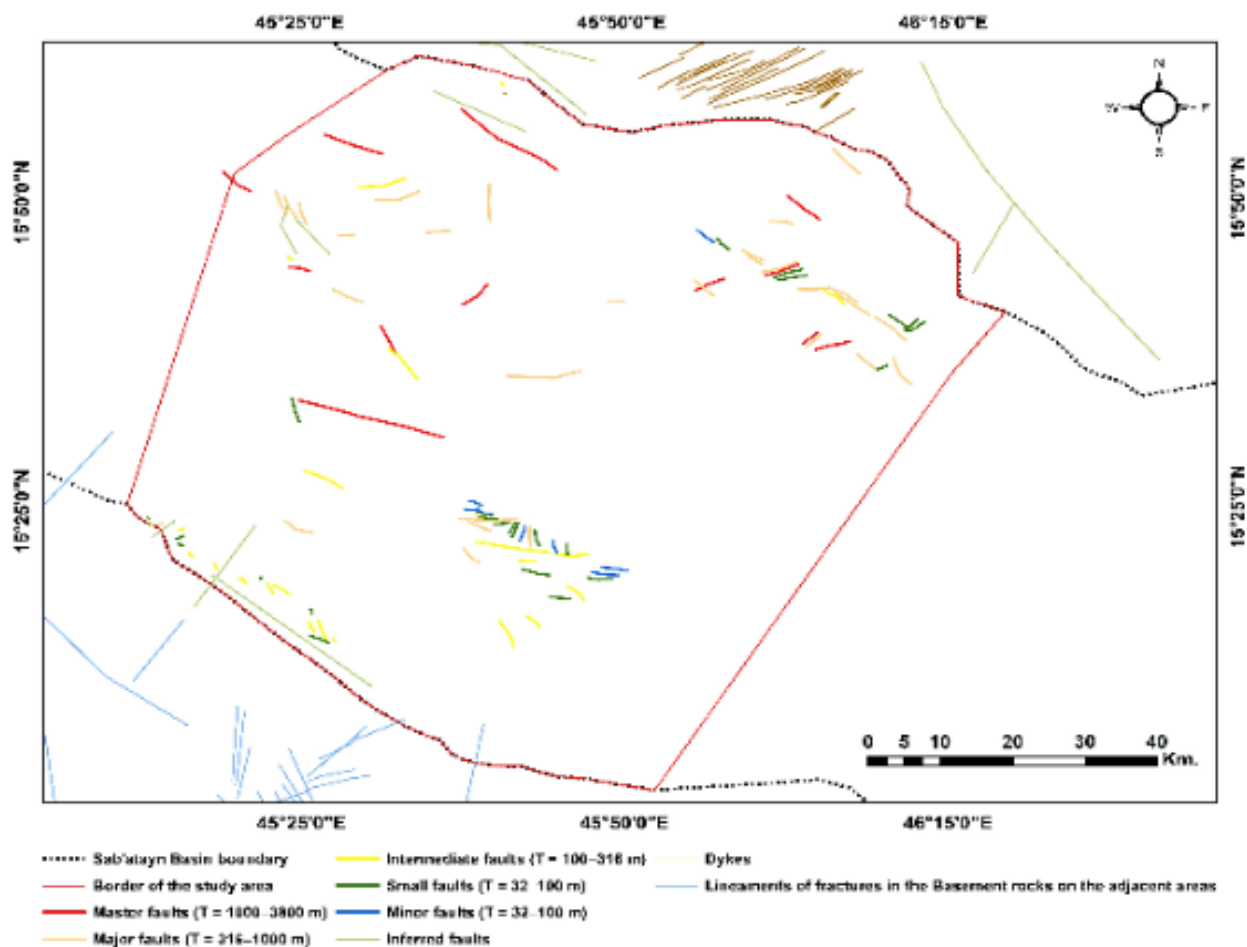


Figure 5. Fault throw distribution map and histogram of the Marib Sub-basin. The dataset reveals a hierarchical displacement pattern, with large throws concentrated along master and major basement-involved normal faults and progressively decreasing displacement toward smaller intra-basinal structures.

4.4. Fault heave

The horizontal slice of displacement, measured perpendicular to the strike, is defined as fault heave. Crucial constraints on extensional stretching across the Marib Sub-basin are provided by these numbers.

$$H = \frac{T}{\tan(\theta)} \quad (1)$$

where:

H = horizontal heave

T = vertical throw

θ = fault dip angle

Dip-slip movement is assumed by this relationship. Strike-slip components are considered negligible.

For net slip:

$$S = \sqrt{T^2 + H^2} \quad (2)$$

where:

S = net slip

T = throw

H = heave

A strict relationship with the structural hierarchy is shown by the heave measurements. The vast bulk of horizontal extension is absorbed by the largest faults. Distributed deformation within the sedimentary layers is handled by the smaller fractures.

A massive range is displayed by the calculated heaves. The hierarchical evolution from deep basement structures up to shallow intra-formational faults is explicitly mirrored. The most extreme heave

values are hosted by master and major NW-SE normal faults. The entire structural framework is anchored by these structures. The lateral pulling and widening of the half-graben were driven entirely by these specific faults.

Distinct displacement categories are formed by the heave distribution (Fig. 6). [Table 3]

Table 3. Fault classification and structural significance based on horizontal heave displacement values.

Fault hierarchy	Heave range	Structural significance
Master faults	High heave values (>1000 m)	Basin-scale normal faults controlling lateral extension and major depocenter development
Major faults	316–1000 m	Significant extensional faults accommodating regional stretching
Intermediate faults	100–316 m	Secondary faults distributing deformation within fault blocks
Small faults	<100 m	Localized brittle deformation and minor accommodation structures

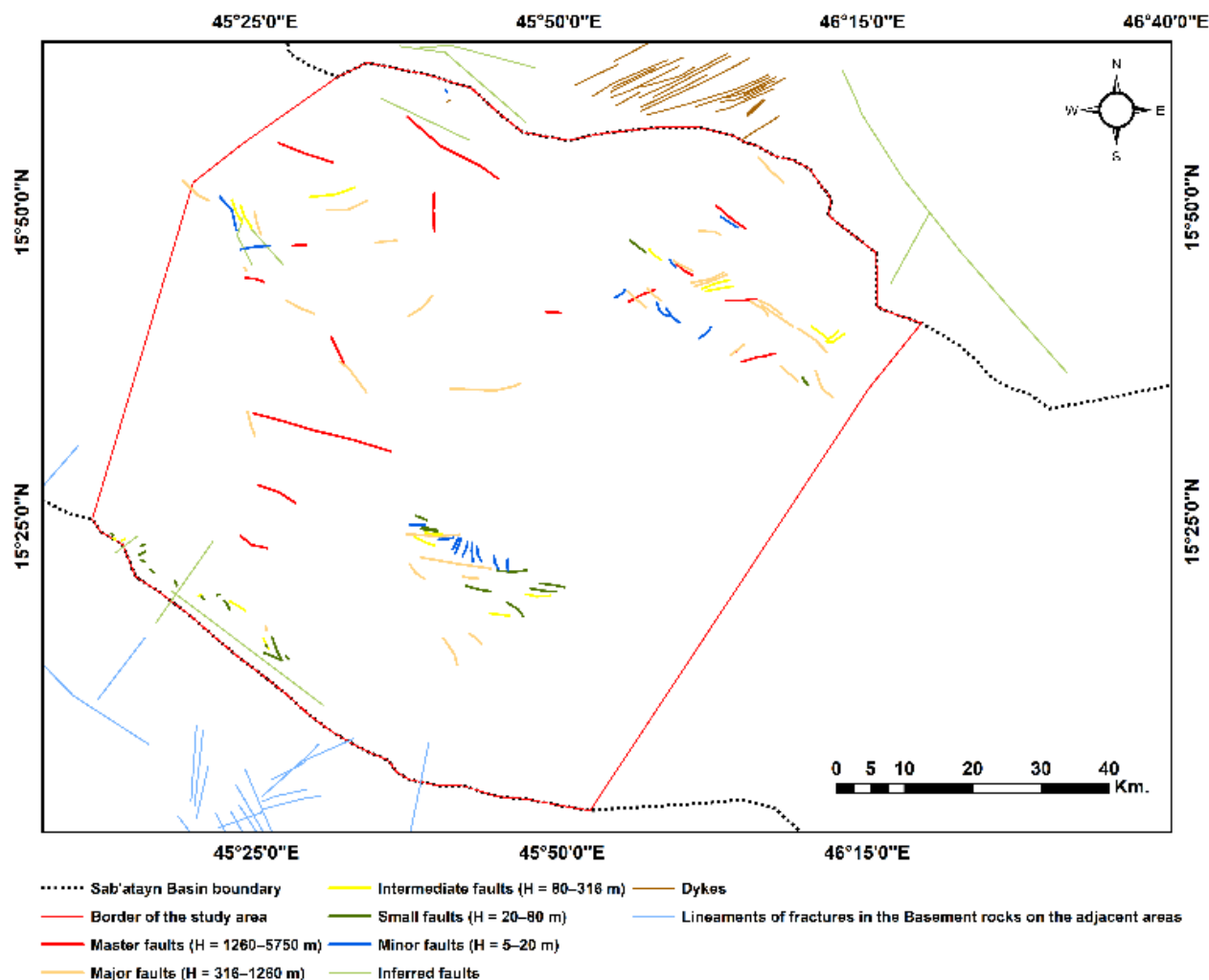


Figure 6. Fault heave distribution map and histogram of the Marib Sub-basin. The distribution shows progressive reduction in horizontal displacement from master and major basin-controlling faults toward intermediate and small subsidiary faults, reflecting hierarchical fault growth and strain partitioning during Jurassic extension.

The most massive horizontal separations are pinned along the basin margins and major structural corridors. The northwestern and southeastern sectors are hit particularly hard. Deep-seated basement faults were reactivated in these exact zones during the Jurassic tearing. Massive horizontal shifting of the syn-rift sediments was produced.

Faults buried in the internal basin exhibit drastically lower heaves. Displacement fades rapidly away from the main corridors. Deformation intensity dropped steadily from the boundary faults down to the minor cracks.

A crystal-clear scaling behavior is demonstrated when heave is plotted against fault size.

Displacement scales up systematically as fault dimensions expand. A disproportionate chunk of the total stretching is eaten by the massive faults. Limited horizontal separation is shared among the numerous smaller cracks. Hierarchical fault growth and displacement partitioning are perfectly matched by this pattern.

4.5. Fault net slip

Throw and heave were used to calculate net slip, following the geometric rules laid out by Ramsay and Huber (1987) and Fossen (2016). Positive yet fluctuating scaling relationships between displacement and hierarchy are revealed by these net-slip values. Deformation proved to be incredibly

heterogeneous. The absolute majority of the tectonic slip was captured by a tiny group of massive faults. Minor amounts of stretching were contributed by the swarm of smaller structures.

The major NW-SE basin-bounding faults hoard the highest net-slip values. The evolution of the Marib

half-graben was steered by these primary extensional structures. Massive displacements are exhibited here due to the compounding of vertical and horizontal movements.

A strict displacement hierarchy is defined by these net-slip numbers (Fig. 7). [Table 4]

Table 4. Fault classification and structural significance based on net-slip displacement values.

Fault hierarchy	Net-slip range	Structural significance
Master faults	>1000 m	Basin-scale faults with maximum cumulative displacement; controlling subsidence and structural architecture
Major faults	316–1000 m	Significant syn-rift structures accommodating regional extension
Intermediate faults	100–316 m	Secondary faults responsible for displacement transfer and segmentation of fault blocks
Small faults	<100 m	Minor structures accommodating localized brittle deformation

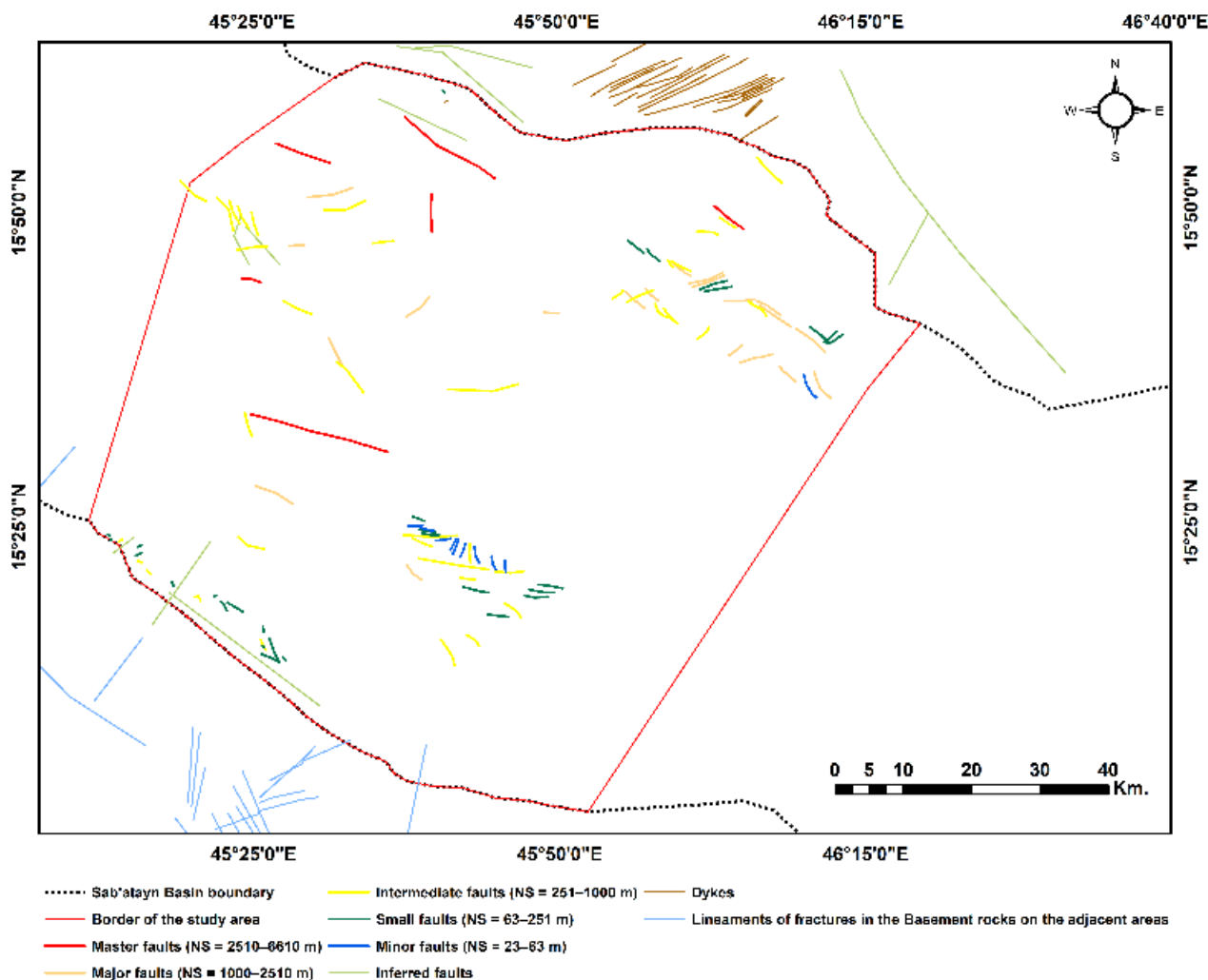


Figure 7. Net-slip distribution map and histogram of faults in the Marib Sub-basin. The distribution highlights the dominance of master and major faults in accommodating cumulative tectonic displacement, while intermediate and small faults represent distributed deformation within the extensional fault network.

The most extreme displacement magnitudes are pinned to deeply rooted basement faults. The northern and southeastern domains host these structures. The main structural boundaries of the half-graben are defined by these high-displacement corridors.

Net-slip values plunge for faults located outside these main zones. Strain intensity dies off away from the master structures. Deformation was passed down through subsidiary faults inside the hanging-wall block.

A positive scaling trend emerges when length is plotted against net slip. Greater cumulative

displacement is accumulated by larger faults. The expected behavior of natural fault systems is followed perfectly by this geometry. Displacement scales up alongside fault growth and linkage.

Strongly localized extensional tearing is confirmed by the net-slip patterns. A few high-displacement faults dominated the basin. A huge population of smaller structures merely accommodated the leftover strain.

4.6. Histograms and scaling relationships

Analyzing the geometric statistics yields critical insights into the distribution, maturity, and growth of the fault population. The histograms for fault length,

throw, heave, and net slip reveal a strong asymmetry, characterized by the dominance of small and intermediate faults and a steep decline in frequency toward larger dimensions. This highly skewed distribution exhibits power-law characteristics commonly observed in natural fault networks. Power-law characteristics are displayed explicitly by these heavily skewed distributions. Natural fault networks exhibit this exact behavior [13]. The constant birth of secondary structures during progressive stretching is reflected by the flood of shorter faults. A massive chunk of the total tectonic strain was absorbed by the few longest, fully mature faults.

Intermediate and small classes claim almost every fault in the length distribution. Master-fault dimensions are reached by only a handful of structures. A self-similar network architecture is demonstrated by this hierarchy. Two master faults (>15 km), twenty major (7–15 km), thirty-eight intermediate (3–7 km), twenty-six small (1–3 km), and fourteen minor faults (<1 km) make up the population. Progressive segmentation, propagation, and linkage drove the basin evolution. Fault growth was clearly achieved through the collision and merging of smaller segments. The instant creation of massive continuous faults did not occur.

Positively skewed distributions are mirrored exactly by the throw, heave, and net-slip histograms. Small displacements characterize most faults. Massive offsets are hoarded by a few structures. The extreme throw and net-slip values are tied directly to the basin-bounding faults. Accommodation space and subsidence were controlled by these specific structures. Limited displacement is shown by the smaller intra-basinal faults. Distributed strain within the sediments is represented here. Fault size and displacement are tied inextricably to structural position and maturity.

The Marib Sub-basin evolved as a basement-involved asymmetric half-graben. Progressive Jurassic continental tearing drove this evolution.

Quantitative proof for progressive fault growth, strain localization, and basin segmentation is provided by these hierarchical distributions. A comprehensive tectonic model is established for the Marib Sub-basin. The broader understanding of extensional mechanics in the Sab'atayn Basin is expanded by these metrics.

4.7. Scaling relationships between fault length and displacement parameters

Positive relationships are demonstrated by the bivariate scaling analysis between fault length and displacement parameters. Progressive growth through slip accumulation and lateral propagation is indicated here. Roughly linear trends are revealed on log-log plots [16]. Geometric scaling rules typical of natural fault systems are followed by these structures [17]. Continued slip accumulation built the larger faults. Less mature or younger segments are represented by the shorter structures.

Disproportionately high vertical displacements were achieved by the largest faults. Long-term activity and regional extension capacity are reflected by this throw-to-length relationship. Horizontal separation scaled up alongside fault propagation. Basin-margin structures absorbed the most extension. Both vertical and horizontal components are combined in the net-slip versus length relationship. A much more complete picture of fault growth is provided. Displacement magnitudes scale up systematically with structural size.

A model of progressive nucleation, propagation, interaction, and linkage is supported heavily by this scaling behavior. The fault system evolved as a highly dynamic network. Mechanical interaction between ancient basement fabrics and young sedimentary faults controlled this evolution. Established fault-growth models are mirrored perfectly by these scaling characteristics. Displacement is accumulated progressively as faults stretch laterally over time [1, 2].

Positive scaling relationships are extracted from the log-log regressions (Fig. 8).

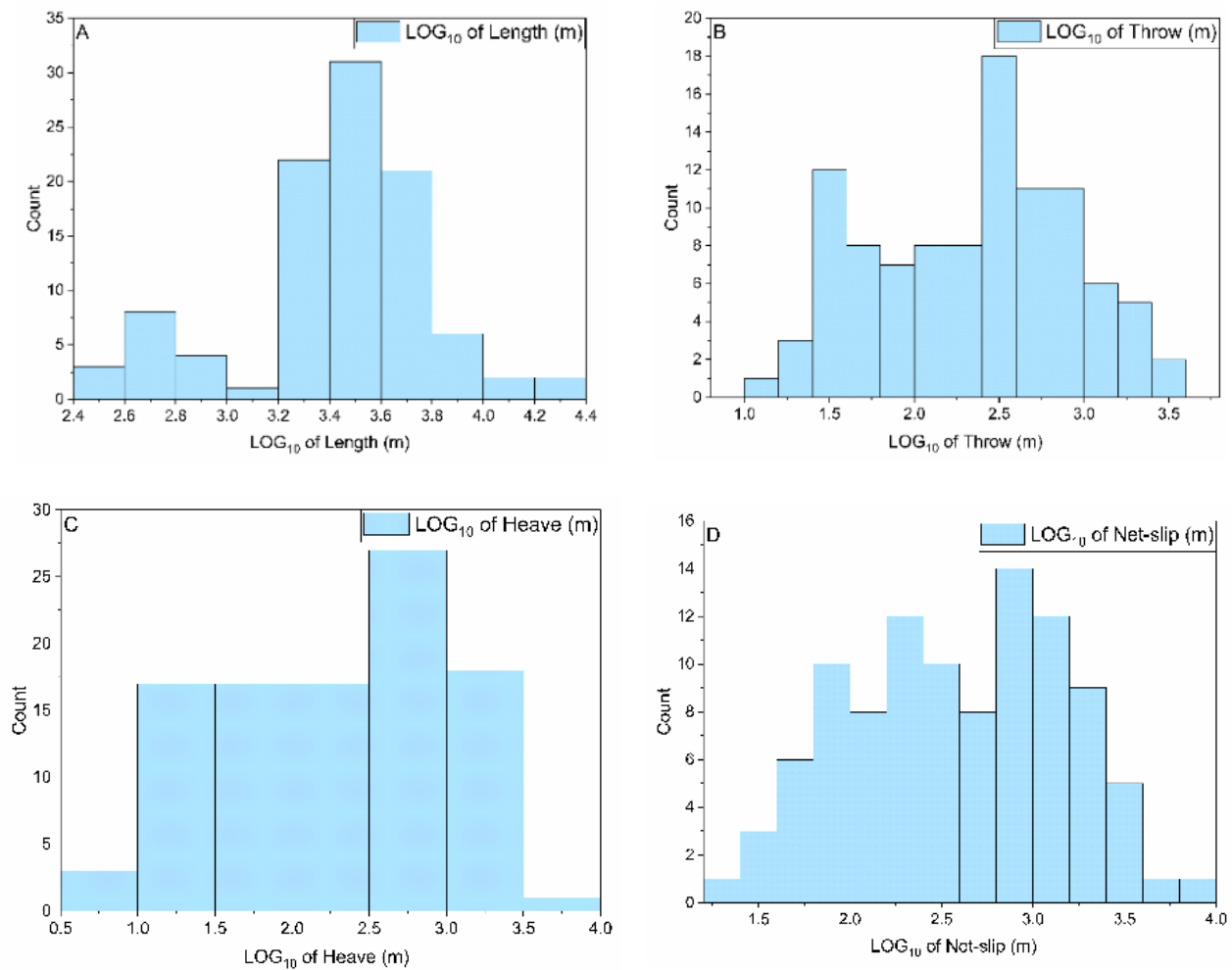


Figure 8. Log–log bivariate relationships among the principal geometric parameters of the faults in the Marib Sub-basin. (A) Fault length versus throw, (B) fault length versus heave, (C) fault length versus net slip, and (D) throw versus heave. Best-fit linear regression lines indicate positive scaling relationships between fault length and displacement parameters, demonstrating that longer faults

generally exhibit greater throw, heave, and net slip. The positive correlation between throw and heave reflects the geometric relationship between the vertical and horizontal components of fault displacement. The moderate scatter around the regression trends suggests natural variability in fault growth, segmentation, displacement accumulation, and structural inheritance within the fault population. Displacement scaled up with fault growth throughout the basin history. Weak to moderate positive correlations are exhibited between length and throw ($R^2 = 0.137$; $r = 0.370$), heave ($R^2 = 0.336$; $r = 0.580$), and net-slip ($R^2 = 0.272$; $r = 0.522$). Displacement variability cannot be explained entirely by fault length. Fault maturity, linkage state, mechanical

stratigraphy, and inherited basement fabrics exert massive control over slip accumulation. Fault interaction and segmentation inject substantial scatter into the data. Moderate scatter surrounds the regression lines.

The absolute strongest correlation is displayed by the throw-heave relationship ($R^2 = 0.518$; $r = 0.720$). A regression slope sitting near unity is observed. Vertical and horizontal slips were accumulated proportionally during the normal faulting events. A mature hierarchical extensional network was produced through progressive propagation and slip accumulation. The vast bulk of basin-scale deformation was absorbed by a few long-lived master

faults. Distributed strain was pushed into the hanging-wall domain by numerous subsidiary fractures. [Table 5]

Table 5. Log-log bivariate regression relationships and correlation coefficients for fault geometric parameters.

Relationship	R ²	Interpretation
Length–Throw	0.137	Weak correlation
Length–Heave	0.336	Moderate correlation
Length–Net slip	0.272	Moderate correlation
Throw–Heave	0.518	Strong correlation

Displacement magnitude cannot be predicted by fault length alone.

4.8. Key results derived from histograms and scaling analysis

- A hierarchical fault population is contained within the Marib Sub-basin. Small and intermediate faults dominate the network. Large displacement structures are rare.
- Massive positive skewness is shown by the length, throw, heave, and net-slip distributions. Power-law behavior typical of tectonic systems is explicitly indicated.
- The absolute majority of displacement is accommodated by a tiny fraction of the faults. Strain localization along major and master structures is confirmed.
- Positive scaling relationships are exhibited between fault length and all displacement parameters. Displacement increases systematically alongside fault growth.
- Single-event formation did not occur. Faults were developed through progressive propagation, segmentation, and ultimate linkage.

- A fully mature extensional system is reflected by the population. Basement-involved faults interacted heavily with younger cover faults during the tectonic evolution.

4.9. Structural architecture of the Marib Sub-basin

A highly hierarchical, mature fault system is revealed to be running through the Marib Sub-basin by the structural data. Regional deformation is unevenly distributed, with a few basin-scale master and major faults accommodating the majority of the strain, while smaller subsidiary structures handle residual strain within the hanging-wall domains. This behavior aligns perfectly with classic normal-fault evolution models [1, 2, 4, 16]. The dominance of NW–SE basement-involved faults indicates that the basin's structural destiny was essentially hardwired by old Precambrian fabrics, shaping the architecture of the asymmetric half-graben (Fig. 9). Merely the shallowest expression of profound crustal deformation is represented by surface fault exposures. This basement-controlled extensional regime shares structural similarities with other major rifts, such as the East African Rift System and the Gulf of Suez, where strain strictly localizes on ancient crustal anisotropies [12, 18–22].

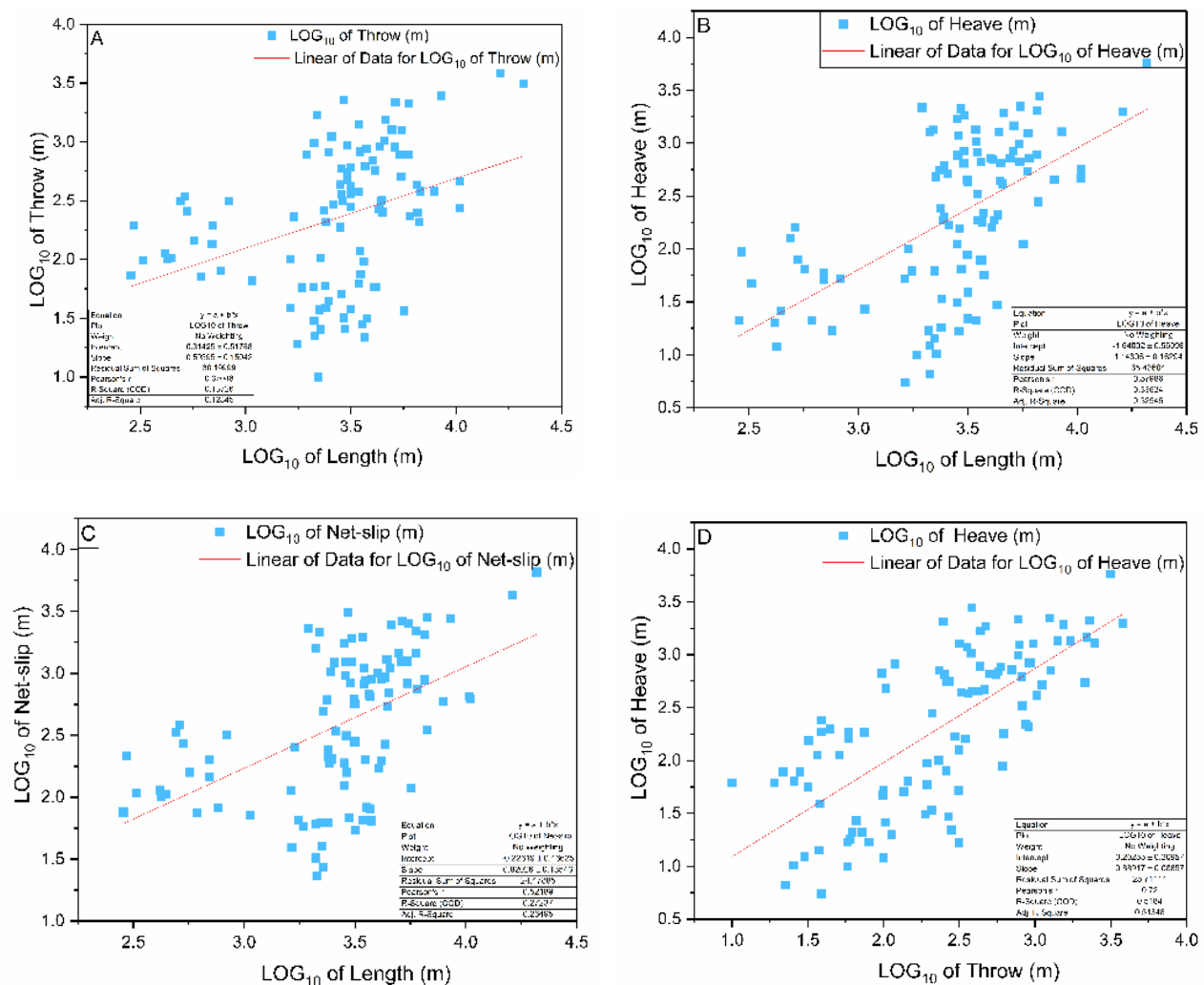


Figure 9. Structural framework and hierarchical fault architecture of the Marib Sub-basin based on integrated surface and sub-surface fault mapping. Map showing the distribution and hierarchical classification of mapped faults in the Marib Sub-basin, including master, major, intermediate, small, and minor faults. Surface and sub-surface faults are distinguished to illustrate differences in structural continuity, fault density, and spatial organization.

4.10. Strain localisation and displacement partitioning

Strain across the Marib Sub-basin is remarkably heterogeneous. The distributions of throw, net slip, and heave reveal severe localization. Although small and intermediate faults numerically dominate the population, the cumulative offset is overwhelmingly hoarded by the massive basin-bounding structures. As the basin evolved, regional extension progressively abandoned the smaller structures, focusing heavily on long-lived master faults instead. This trajectory is strongly backed by the positive scaling relationships charted between displacement

and fault length, a feature characteristic of mature continental rifts [1, 23, 24]. Furthermore, localized positive flower-like structures identified in the northeastern sector of the basin suggest occasional oblique deformation or transpressional adjustments occurring along inherited basement lines during shifting stress regimes.

4.11. Implications for fault growth and basin evolution

The idea that massive faults were formed instantaneously is explicitly ruled out by our scaling data. Faults propagated systematically, which is confirmed by the log-log correlations. Slip was

accumulated over time while isolated segments were merging into continuous structures spanning the basin [16, 17]. Real-world geological complexity is highlighted by the scatter present in our data, however. Mechanical stratigraphy, relay zones, and the stubborn reactivation of basement rocks had to be navigated by fault growth. The scaling trends we found mirror those in the North Sea, the Gulf of Suez, and East Africa [18, 20, 21]. Yet, the fault network was bullied more by Precambrian basement inheritance than by simple length-driven growth. This is suggested by the moderate correlations found specifically in Marib. The smaller faults were progressively abandoned by strain to hyper-focus on the master structures. A classic evolutionary sequence starting from distributed brittle fracturing and ending with integrated border-fault dominance was followed [2, 18, 24]. This Mesozoic history is shared by other sectors in the Sab'atayn Basin (such as Al-Jawf and Shabwah). Far superior strain localization and highly pronounced hierarchical fault development were created by the rigid NW–SE basement control of Marib, though.

4.12. Regional tectonic significance

A premier example of a basement-influenced intracontinental rift is structurally represented by the Marib Sub-basin. Gondwana's initial fragmentation triggered this. Extensional tectonics are firmly pointed to by the hierarchical NW–SE normal faults and the deep asymmetric half-graben geometry. Theories claiming that strike-slip pull-apart processes dominated the basin's formation are shut down by this. Straight from the Precambrian basement into the Jurassic succession, those NW–SE fabrics survived. They were heavily dictated by the Najd Fault System and the boundary of the Abbas Terrane–Al-Bayda Island Arc. Millions of years of subsequent stretching and fault nucleation were directed by ancient crustal scars. This is similar to what happened in the East African Rift or the Gulf of Suez [12, 21, 22]. The clearest record of structural inheritance among all Arabian extensional basins is arguably preserved by Marib. Fundamental fault-growth mechanisms are shared by it with mature

continental rifts globally, despite differences seen in lithospheric thickness and regional geodynamic settings. Regional tectonics is not the only thing this is about. Syn-rift accommodation space and sediment dispersal were also dictated where strain was localized by these deep master faults. The petroleum systems of the basin were mapped out by them. Old qualitative regional models are replaced with a rigorous structural framework concerning southern Arabia's Jurassic rift evolution by quantifying this hierarchy.

4.13. Implications for hydrocarbon systems

What this hierarchical fault architecture means for the petroleum system is impossible to ignore. Primary vertical highways for hydrocarbon migration were likely provided by the deeply rooted master faults during the Jurassic extension. Accumulation patterns were heavily altered by the progressive segmentation and growth of subsidiary faults meanwhile. Reservoir compartmentalization was promoted by this [25, 26]. Where structural traps formed was governed effectively by the basement-controlled framework. Overall fault-seal integrity was dictated by it as well. A direct, highly valuable tool is handed to future exploration teams by quantifying the fault connectivity, displacement partitioning, and master faults in this study. Reservoir compartmentalization, evaluating structural traps, and tracking migration pathways across the Sab'atayn Basin can be predicted using it.

4.14. Limitations and uncertainties

While the integration of surface and subsurface datasets significantly improves the robustness of this study and reduces geological ambiguity, certain limitations and uncertainties remain. Relying primarily on 2D seismic reflection profiles may introduce minor uncertainties in mapping the exact lateral continuity and tip-line locations of smaller subsurface faults compared to high-resolution 3D seismic data. Additionally, measuring fault heave and throw from seismic sections inherently carries velocity-model and depth-conversion uncertainties. However, the consistent power-law scaling relationships observed across the entire dataset

suggest that these data limitations do not affect the fundamental validity of the structural hierarchy and the basin-scale tectonic interpretations presented.

4.15. Validation

To validate the results and ensure data reliability, the structural geometries extracted from subsurface seismic interpretations were systematically cross-referenced with surface field mapping and well-log data. The strong correlation between shallow surface fault orientations and deep subsurface basement fabrics confirms the accuracy of the structural framework. Furthermore, a sensitivity analysis of the geometric parameters reveals that the positive log-log scaling relationships (e.g., throw vs. heave, $R^2 = 0.518$) align perfectly with globally established empirical scaling laws for natural extensional fault systems. This alignment serves as a robust internal validation for the geometric quantification techniques applied in this study.

5. Conclusions

Based on the integrated quantitative structural analysis of the Marib Sub-basin, the following key conclusions are drawn:

1. The Marib Sub-basin is characterized by a mature, highly hierarchical extensional fault network.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions

S.A.G., M.A., F.A.A., S.E., S.M.A.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization.

Data Availability Statement

The seismic and geological datasets generated and/or analyzed during the current study are not publicly available due to confidentiality agreements with the Ministry of Oil and Minerals, Republic of Yemen, but may be available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI Use Disclosure

During the preparation of this work, the authors used artificial intelligence tools solely to improve readability, language, and formatting. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the final content of the publication.

The 100 mapped faults naturally group into master, major, intermediate, small, and minor structures.

2. Displacement distributions exhibit pronounced positive skewness, indicating highly efficient strain partitioning. Regional deformation is overwhelmingly accommodated by a few deeply rooted master faults, while smaller structures handle secondary intra-basinal strain.
3. Fault growth occurred through progressive nucleation, lateral propagation, interaction, and segment linkage, as evidenced by the robust positive scaling relationships between fault length and displacement parameters (throw, heave, and net slip).
4. The basin evolved as an asymmetric, basement-controlled half-graben. The dominant NW-SE fault orientations were strictly guided by the reactivation of pre-existing Precambrian basement fabrics during Jurassic continental extension.
5. This quantitative framework provides critical predictive insights for hydrocarbon exploration, specifically for identifying deep structural traps, assessing fault-seal integrity, and evaluating reservoir compartmentalization within the Sab'atayn Basin.

REFERENCES

- [1] P. A. Cowie and C. H. Scholz, “Displacement-length scaling relationship for faults: data synthesis and discussion,” *Journal of Structural Geology*, vol. 14, pp. 1149–1156, 1992, [https://doi.org/10.1016/0191-8141\(92\)90066-6](https://doi.org/10.1016/0191-8141(92)90066-6)
- [2] N. H. Dawers, M. H. Anders, and C. H. Scholz, “Growth of normal faults: Displacement-length scaling,” *Geology*, vol. 21, pp. 1107–1110, 1993, [https://doi.org/10.1130/0091-7613\(1993\)021<1107:GONFDL>2.3.CO;2](https://doi.org/10.1130/0091-7613(1993)021<1107:GONFDL>2.3.CO;2)
- [3] H. Fossen, *Structural Geology*, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 2016.
- [4] C. Childs, T. Manzocchi, J. J. Walsh, C. G. Bonson, A. Nicol, and M. P. Schöpfer, “A geometric model of fault zone and fault rock thickness variations,” *Journal of Structural Geology*, vol. 31, pp. 117–127, 2009, <https://doi.org/10.1016/j.jsg.2008.08.009>
- [5] P. Redfern and J. A. Jones, “The interior rifts of the Yemen-analysis of basin structure and stratigraphy in a regional plate tectonic context,” *Basin Research*, vol. 7, pp. 337–356, 1994, <https://doi.org/10.1111/j.1365-2117.1995.tb00121.x>
- [6] Z. R. Beydoun, M. L. As-Saruri, and R. S. Baraba, “Sedimentary basins of the Republic of Yemen: their structural evolution and geological characteristics,” *Revue de l’Institut Français du Pétrole*, vol. 51, pp. 763–775, 1996, <https://doi.org/10.2516/ogst.1996049>
- [7] S. A. Ghareb, S. A. Ali, H. S. Aldharab, and J. Ikbāl, “Analysis of major surface structural features in Marib Sector, Sab’atayn Basin, Yemen: Implications of tectonic evolution,” *Bulletin of Pure and Applied Sciences – Geology*, vol. 38F, no. 1, 2019, <https://doi.org/10.5958/2320-3234.2019.00004.0>
- [8] S. A. Ghareb, S. A. Ali, D. Bucković, H. S. Aldharab, and M. Ahmad, “Recording Jurassic microfossils from Jabal Al-Balaq at Marib Governorate, Yemen,” *Bulletin of Pure and Applied Sciences – Geology*, vol. 41F, no. 2, pp. 228–250, 2022, <https://doi.org/10.5958/2320-3234.2022.00019.1>
- [9] R. J. Stern, P. R. Johnson, A. Kröner, and B. Yibas, “Neoproterozoic ophiolites of the Arabian-Nubian shield,” *Developments in Precambrian Geology*, vol. 13, pp. 95–128, 2004, [https://doi.org/10.1016/S0166-2635\(04\)13003-X](https://doi.org/10.1016/S0166-2635(04)13003-X)
- [10] A. C. Ellis, H. M. Kerr, C. P. Cornwell, and D. O. Williams, “A tectono-stratigraphic framework for Yemen and its implications for hydrocarbon potential,” *Petroleum Geoscience*, vol. 2, no. 1, pp. 29–42, 1996, <https://doi.org/10.1144/petgeo.2.1.29>
- [11] C. K. Morley, “Evolution of large normal faults: Evidence from seismic reflection data,” *AAPG Bulletin*, vol. 86, no. 6, pp. 961–978, 2002, <https://doi.org/10.1306/61EEDBFC-173E-11D7-8645000102C1865D>
- [12] W. Bosworth, P. Huchon, and K. McClay, “The Red Sea and Gulf of Aden basins,” *Journal of African Earth Sciences*, vol. 43, no. 1–3, pp. 334–378, 2005, <https://doi.org/10.1016/j.jafrearsci.2005.07.020>
- [13] E. Bonnet, O. Bour, N. E. Odling, P. Davy, I. Main, P. Cowie, and B. Berkowitz, “Scaling of fracture systems in geological media,” *Reviews of Geophysics*, vol. 39, no. 3, pp. 347–383, 2001, <https://doi.org/10.1029/1999RG000074>
- [14] D. C. P. Peacock and D. J. Sanderson, “Displacements, segment linkage and relay ramps in normal fault zones,” *Journal of Structural Geology*, vol. 13, no. 6, pp. 721–733, 1991, [https://doi.org/10.1016/0191-8141\(91\)90033-F](https://doi.org/10.1016/0191-8141(91)90033-F)
- [15] J. G. Ramsay and M. I. Huber, *The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures*. London, U.K.: Academic Press, 1987.
- [16] J. J. Walsh, A. Nicol, and C. Childs, “An alternative model for the growth of faults,” *Journal of Structural Geology*, vol. 24, no. 10, pp. 1669–1675, 2002, [https://doi.org/10.1016/S0191-8141\(01\)00165-1](https://doi.org/10.1016/S0191-8141(01)00165-1)
- [17] Y. S. Kim and D. J. Sanderson, “The relationship between displacement and length of faults: a review,” *Earth-Science Reviews*, vol. 68, no. 3–4, pp. 317–334, 2005, <https://doi.org/10.1016/j.earscirev.2004.06.003>
- [18] R. B. Færseth, “Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea,” *Journal of the Geological Society*, vol. 154, no. 6, pp. 997–1014, 1997, <https://doi.org/10.1144/gsjgs.153.6.0931>
- [19] A. M. Roberts, G. Yielding, N. J. Kusznir, I. Walker, and D. Dorn-Lopez, “Quantitative analysis of the structural evolution of the North Sea Rift,” *Marine and Petroleum Geology*, vol. 16, no. 5, pp. 461–477, 1999.
- [20] A. I. Younes and K. McClay, “Development of accommodation zones in the Gulf of Suez-Red Sea rift, Egypt,” *AAPG Bulletin*, vol. 86, no. 6, pp. 1003–1026, 2002, <https://doi.org/10.1306/61EEDC10-173E-11D7-8645000102C1865D>
- [21] C. K. Morley, “Patterns of displacement along large normal faults: implications for basin evolution and fault propagation, based on examples from East Africa,” *AAPG Bulletin*, vol. 83, no. 4, pp. 613–634, 1999, <https://doi.org/10.1306/00AA9C0A-1730-11D7-8645000102C1865D>

- [22] J. Chorowicz, “The East African rift system,” *Journal of African Earth Sciences*, vol. 43, no. 1–3, pp. 379–410, 2005, <https://doi.org/10.1016/j.jafrearsci.2005.07.019>
- [23] C. H. Scholz, *The Mechanics of Earthquakes and Faulting*, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 2002.
- [24] C. J. Ebinger, “Continental break-up: The East African perspective,” *Astronomy & Geophysics*, vol. 46, no. 2, pp. 2.16–2.21, 2005, <https://doi.org/10.1111/j.1468-4004.2005.46216.x>
- [25] U. S. Allan, “Model for hydrocarbon migration and entrapment within faulted structures,” *AAPG Bulletin*, vol. 73, no. 6, pp. 803–811, 1989, <https://doi.org/10.1306/44B4A271-170A-11D7-8645000102C1865D>
- [26] G. Yielding, B. Freeman, and D. T. Needham, “Quantitative fault seal prediction,” *AAPG Bulletin*, vol. 81, no. 6, pp. 897–917, 1997, <https://doi.org/10.1306/522B498D-1727-11D7-8645000102C1865D>
- [27] A. N. Al-Dujaili, “Analysis of in-situ stress and well trajectory in carbonate and sandstone reservoirs. A case study of Mishrif and Zubair Formations in the West Qurna Oilfield, Southern Iraq,” *Iraqi Journal of Science*, 2025, <https://doi.org/10.24996/IJS.2025.66.5.12>