



Research Article

Extensional Origin and Basement Control of the Marib Sub-Basin, Yemen: Evidence from 2D Seismic and Field Geological Data

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Abstract: The structural evolution and tectonic origins of the Marib Sub-basin, a major Mesozoic rift system within Yemen's Sab'atayn Basin, remain debated. This study aims to resolve this by reconstructing the basin's structural architecture and determining the role of inherited Precambrian fabrics. We integrated detailed geological field observations with subsurface 2D seismic reflection data to map fault geometries. The structural analysis reveals an asymmetric, NW–SE-trending half-graben, where master boundary faults downthrow the crystalline basement by more than 2,800 m. This geometry was strongly controlled by inherited Precambrian basement fabrics, specifically the Najd Fault System and the boundary separating the Abbas Gneiss and Al-Bayda Island Arc terranes. Seismic interpretations demonstrate a two-tiered architecture: deep basement-rooted normal faults, and a shallow detached system of listric faults within the Sab'atayn evaporites. Crucially, positive flower structures are confined strictly to the northeastern sector within the syn-rift succession, representing localized transtensional adjustments rather than basin-scale strike-slip kinematics. We conclude that the Marib Sub-basin evolved as an extension-dominated intracontinental rift. This updated framework provides significant additive value by clarifying structural inheritance mechanisms, offering a refined blueprint for understanding similar structurally inherited rifts and optimizing hydrocarbon exploration across the southern Arabian Plate.

Keywords: Marib Sub-basin, Structural evolution, Basement inheritance, Half-graben, Rift tectonics.

1 Introduction

Understanding a rift basin means piecing together surface geology with subsurface geophysics. It is the only practical way to untangle the complex structural architecture left by repeated phases of fault growth,

linkage, and reactivation. Situated in Yemen's west-central Sab'atayn Basin, the Marib Sub-basin (Fig. 1) provides an excellent setting to see exactly how ancient crustal flaws dictate younger extensional deformation.

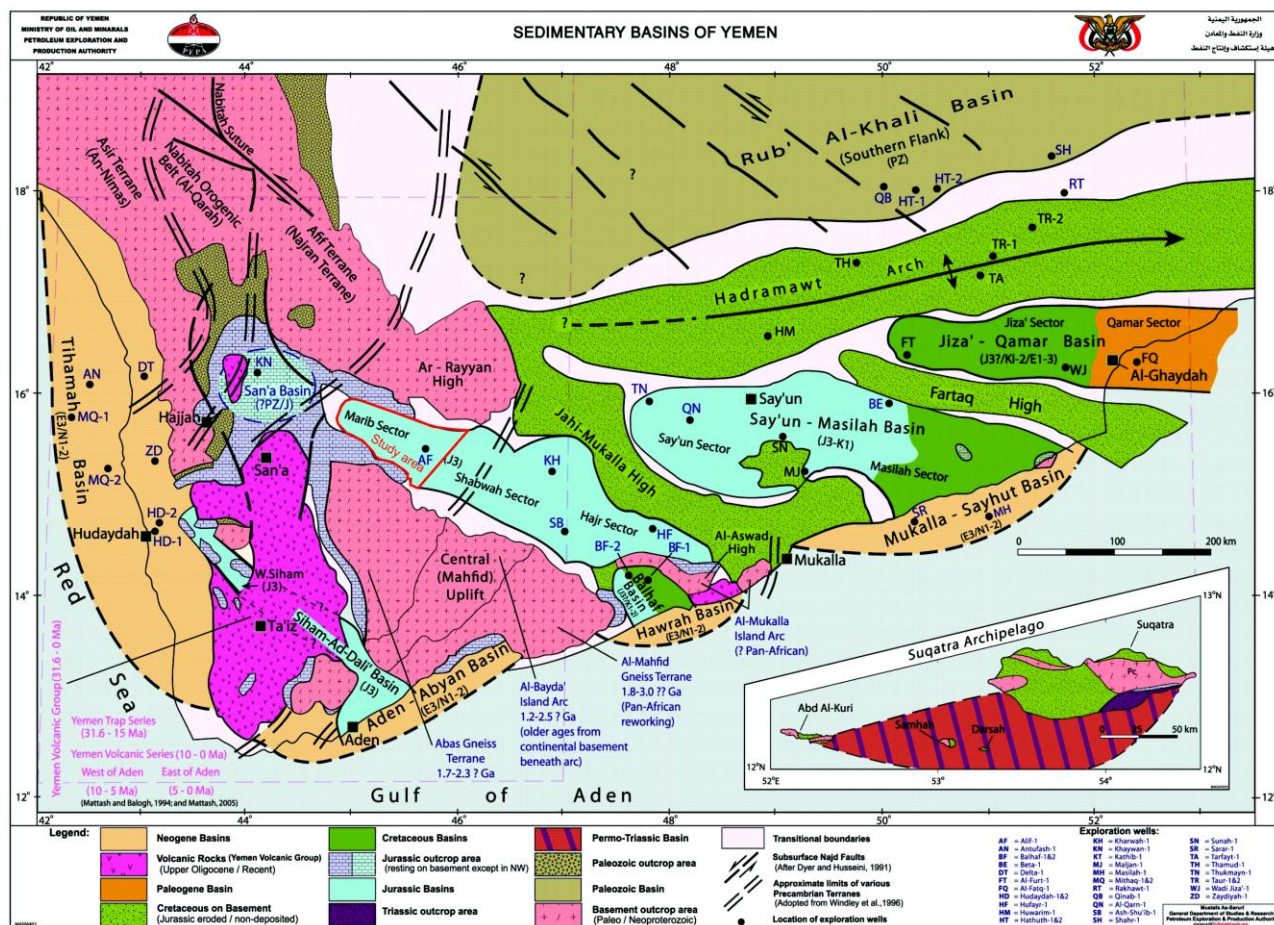


Figure 1. Regional location map of Yemen showing the Sab'atayn Basin and Marib Sub-basin.

Inherited basement structures typically exert massive control over fault geometry, sedimentation, and strain during continental extension [1–4]. As a massive NW–SE-trending half-graben (Fig. 2), Marib holds a

clear record of Phanerozoic tectonics. It preserves evidence of repeated extension, isolated inversion, and fault reactivation [5, 6].

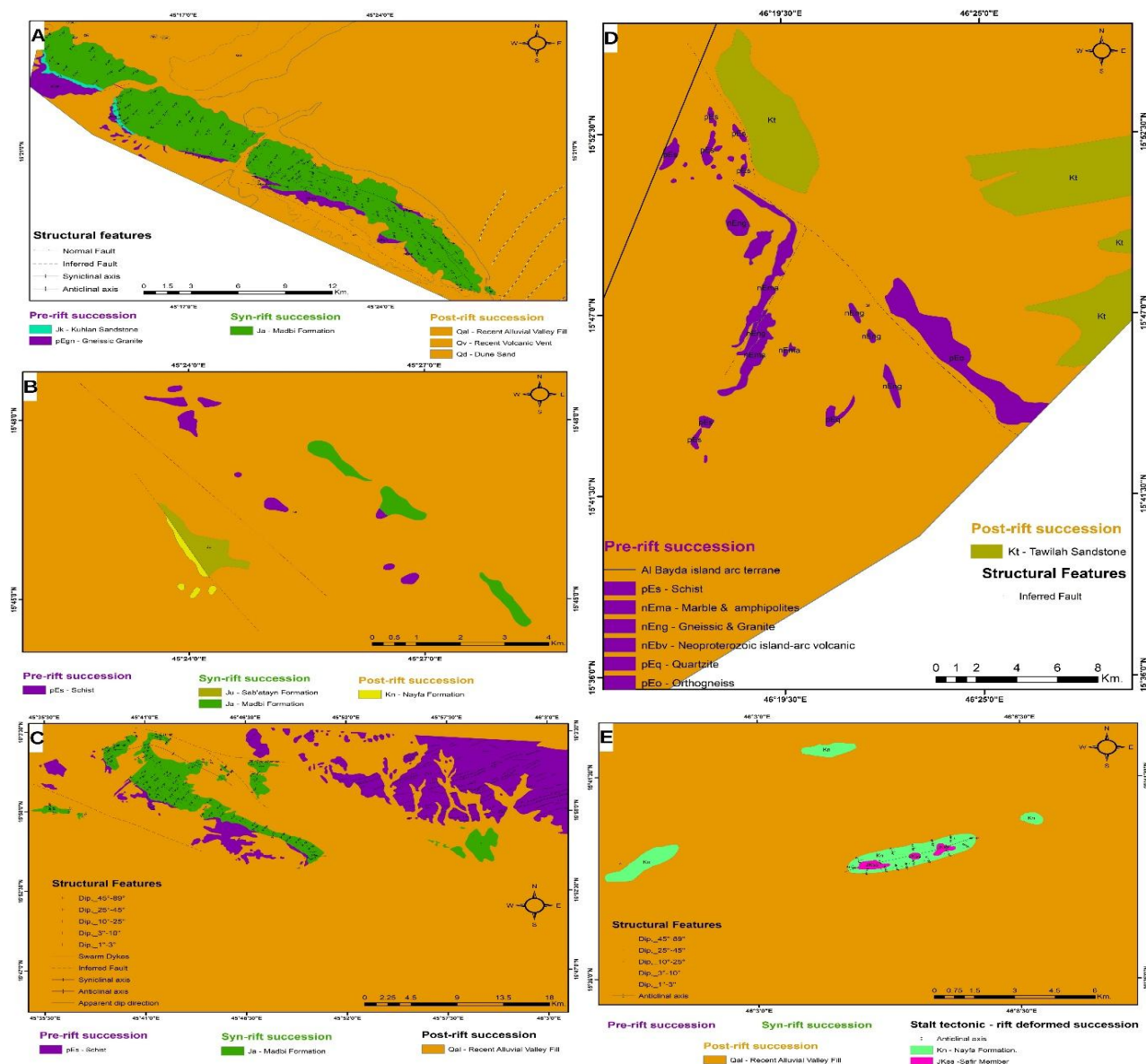


Figure 2. Integrated geological and tectonic maps of representative structural domains in the Marib Sub-basin showing the spatial relationships between Precambrian basement terranes, syn-rift sedimentary units, igneous intrusions, and major fault systems. The maps illustrate the distribution of lithological units and surface structural features.

Industry teams have heavily explored the sub-basin for hydrocarbons [5, 7]. Yet most of those studies stayed tightly focused on petroleum systems, stratigraphic frameworks, or highly localized structures. What we lack is a basin-wide synthesis. By tying field observations to modern seismic interpretations, we can finally reconstruct the area's structural architecture. That integrated framework does more than just solve the Marib Sub-basin's history. It refines tectonic models for the entire

southern Arabian Plate and helps explain structurally inherited continental rifts globally.

Accordingly, this study aims to: (1) determine the role of inherited Precambrian basement fabrics in controlling Jurassic rifting; (2) evaluate whether the Marib Sub-basin evolved as a pull-apart basin or an extension-dominated half-graben; and (3) assess the tectonic significance of localized positive flower structures within the overall structural evolution of the basin.

2. Geological Setting

The Precambrian basement surrounding the basin carries a heavy tectonic imprint from the Pan-African Orogeny and the assembly of the Arabian–Nubian Shield. You can find ductile shear zones, folded quartz veins, ophiolites, and mafic dyke swarms scattered through the rocks. The basement also hosts massive crustal features like the Najd Fault System and the boundary dividing the Abbas Gneiss Terrane from the Al-Bayda Island Arc Terrane [8–10]. Across the Arabian Plate, geologists recognize these inherited fabrics as the primary forces guiding where and how younger extensional faults develop.

2.1. Lithostratigraphic and Tectonostratigraphic Architecture

Sedimentary thickness in the Marib Sub-basin fluctuates wildly, both laterally and vertically. Syndepositional faulting drove these shifts, aided by the constant reactivation of old basement structures. We can divide the basin fill into three main

tectonostratigraphic intervals that log the rift's initiation, expansion, and post-rift decay.

Take the northwestern margin at Al-Kanayis. Here, large NW–SE-trending normal faults pushed the Precambrian crystalline basement straight up to the surface. This uplift ties into a major regional unconformity; every sedimentary unit older than the Middle Callovian is entirely missing. The Shuqrah Formation sits directly on the Precambrian rock, cushioned only by a thin (~5 m) transgressive basal sandstone (Fig. 3). Yet over at Jabal Al-Alam Al-Abiyadh, the Kuhlan Formation vanishes. These stratigraphic gaps highlight extreme spatial variations in sediment deposition and timing during the early stages of rifting. The rock record shows clearly that inherited structural flaws controlled subsidence, directed sediment routing, and dictated fault activity, causing the sub-basin to evolve diachronously.



Figure 3. Basement uplift and unconformity at Al-Kanayis.

Walking the Abbas Terrane exposes a heavily deformed Precambrian basement. The outcrops are full of folded quartz veins, ductile shear zones, recumbent folds, reverse faults, and ophiolitic assemblages. Dense NE–SW-trending dyke swarms

cluster near the suture zone (Fig. 4). The quartz veins and surrounding shear zones record multiple waves of deformation, leaving behind superimposed folds and steeply dipping fabrics.

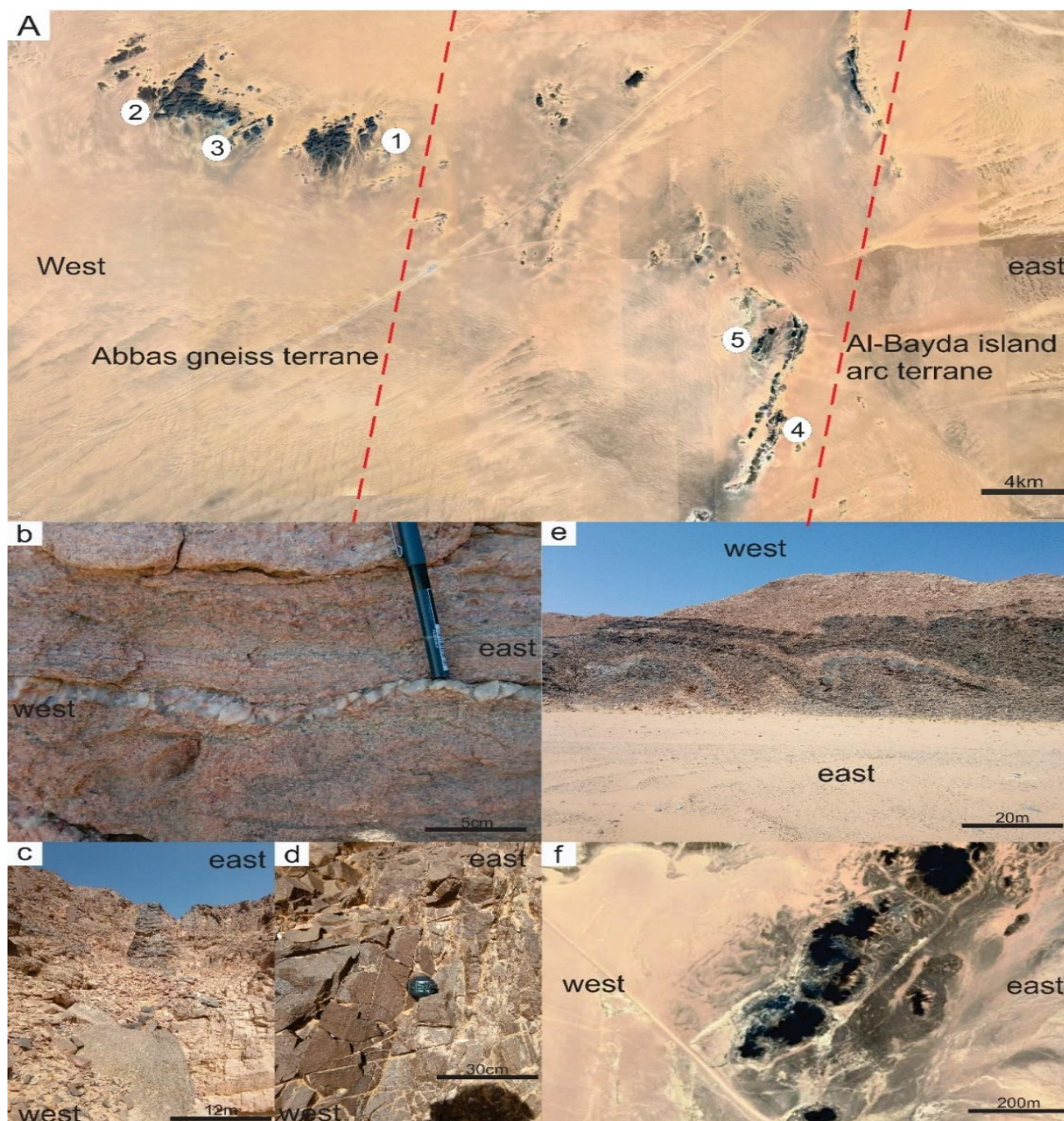


Figure 4. Abbas Terrane, Al-Bayda island arc, suture zone, and field photographs (folds, dykes, quartz veins, ophiolite). (a) Google Earth photograph for Abbas, Al-Bayda Island arc, and zone sutures. (b) Folded quartz vein and shearing zone associated with NE- and NW-oriented veins that dip steeply west, deformed by multi-phases of folding. (c & d) Swarm dykes intersect with the suture zone and have a NE–SW direction. (e) Recumbent folds and reverse fault in the eastern side of Ath-Thanyiah ridge. (f) Volcanic craters, basalt flows, and ophiolitic rocks on the western side of Ath-Thanyiah metamorphosed succession trending northeast. Numbered localities refer to: {1} folded quartz vein and shearing zone; {2 and 3} swarm dykes trending NE–SW; {4} large-scale two-generation folds in Ath Thanyiah metamorphic rocks; {5} ophiolitic assemblage.

Those dyke swarms strike consistently NE–SW, preferring to intrude along inherited basement discontinuities (Fig. 5).

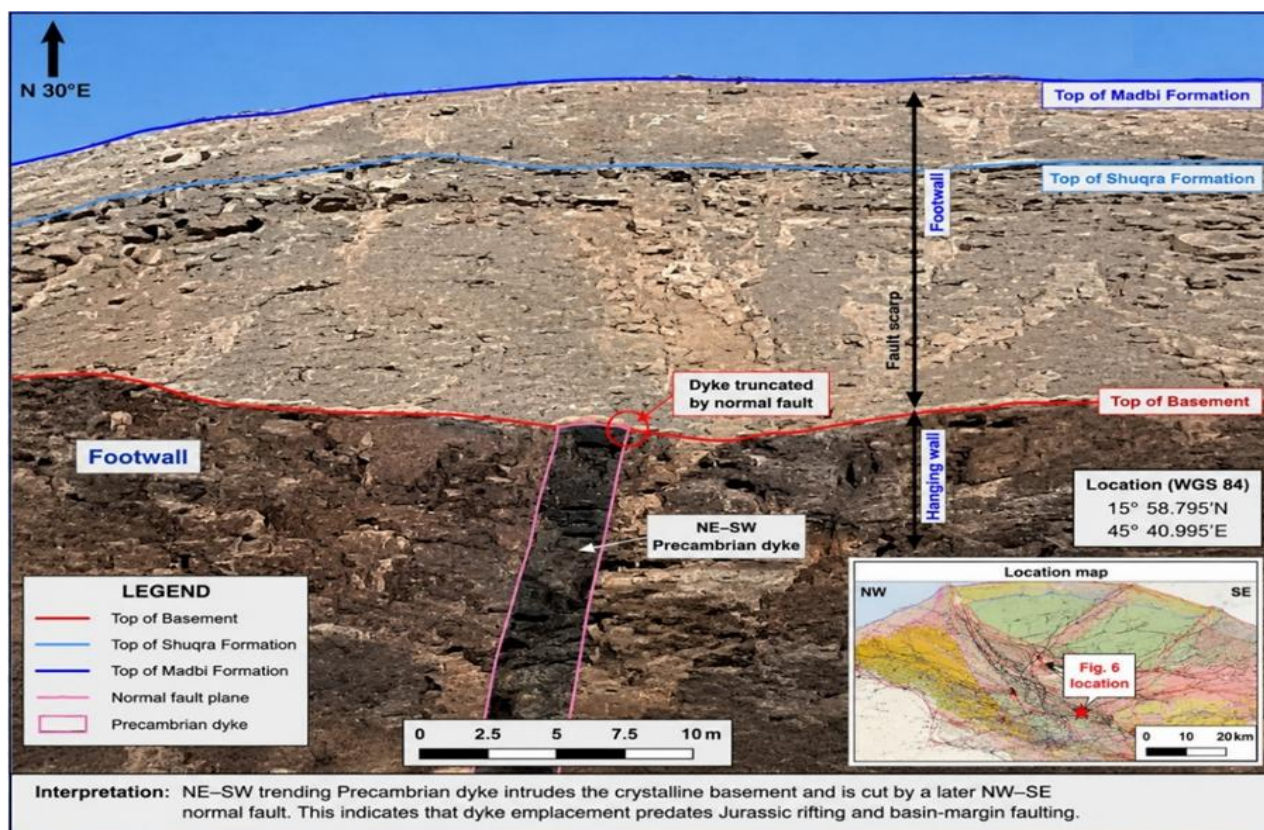


Figure 5. NE-SW dykes truncated by NW-SE normal faults.

Their steady orientation, spatial continuity, and proximity to the suture zone point to massive cumulative sinistral displacement along the central basement fault system. When you look at the dykes alongside the shear fabrics and folded basement rocks, it is obvious this fault system shifted repeatedly long before Mesozoic rifting began.

Structural geometries mapped along the southern and northern monoclines (Fig. 6) confirm this, showing how deep-seated structures shaped the overlying cover. Ultimately, the preserved basement architecture provided a rigid template that dictated fault locations and guided the Marib Sub-basin's entire evolution.

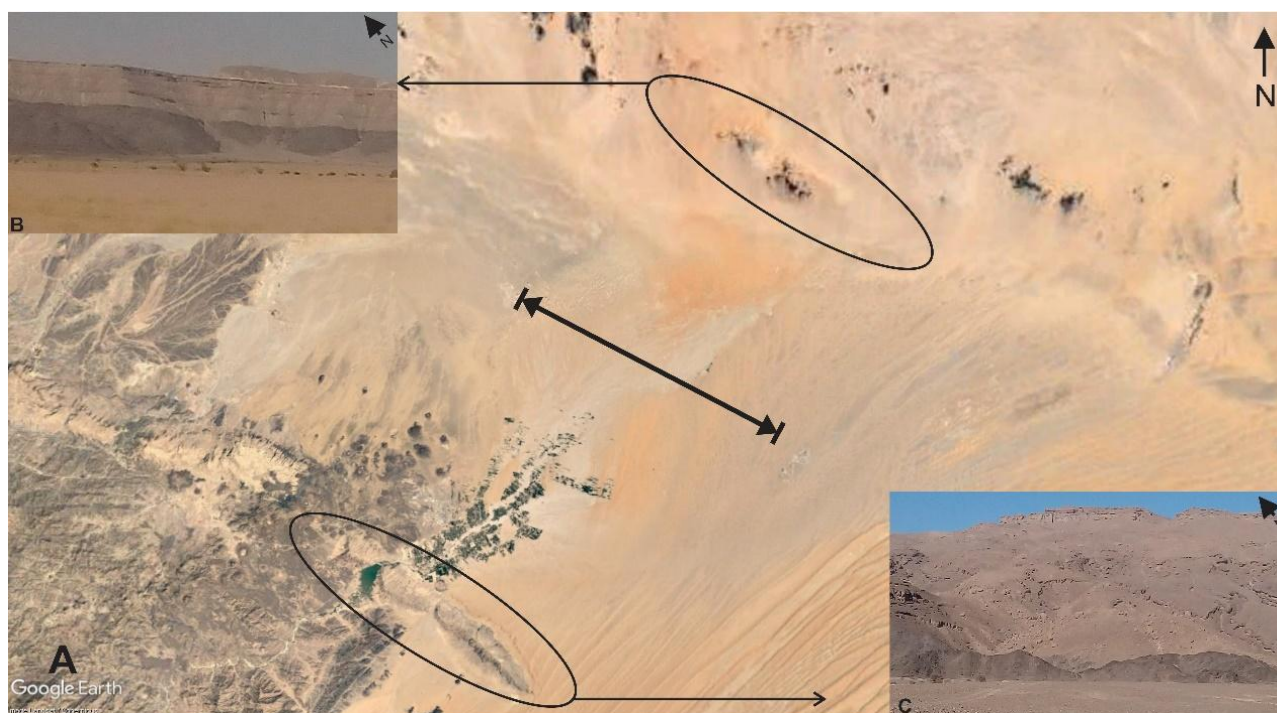


Figure 6. Southern and northern monoclines, basin geometry, and field photographs. (a) Satellite image showing the entire area. (b) Field photograph at the front fault slip on the hanging wall in the northern margin (Al-Alam area). (c) Field photograph at the front fault slip on the hanging wall in the northern margin (Al-Balaq area)

3. Data and Methodology

3.1. Data Sets and Methodology

To map the sub-basin's structural framework, this study pairs field geology with subsurface seismic interpretations. Linking surface mapping, seismic data, quantitative structural analysis, and 3D visualization locks down the basin's geometry and kinematics. Marrying physical rock data with seismic profiles remains the most reliable way to untangle fault architecture in complex rifts [10, 12].

3.1.1. Geological Field Investigations

We targeted our fieldwork at the primary structural exposures: Jabal Al-Balaq Al-Qibili, Jabal Al-Balaq Al-Awsat, Jabal Al-Balaq Ash-Sharqi, Al-Kanayis, and the northern Al-Alam area (refer to Fig. 2). These sites offer superb, clean views of Precambrian basement rocks, sedimentary successions, and major fault zones.

Using standard techniques [10, 11, 13], we mapped fault planes, slip data, fracture networks, bedding attitudes, fold geometries, and stratigraphic contacts. Fault kinematics, cross-cutting relationships, and

basement-cover interactions received special attention so we could nail down the relative timing of deformation. We then ran statistical analyses on the dataset using lower-hemisphere equal-area stereonet to isolate the main fault sets, fracture orientations, and regional stress patterns [14].

3.1.2. Seismic Sections and Structural Integration

For the subsurface, we relied on a network of 2D seismic lines covering the entire Marib Sub-basin. This includes regional dip and strike profiles (C-CS-1, S&SE-CS-1, SE-SS-2, NW-SS-1, NW-SS-2, NW-SS-3, NW-SS-4, NW-SS-5, and NE-CS), which provide continuous imaging of the basin's shape.

Industry exploration teams previously interpreted these lines. However, we independently re-evaluated and validated every structural horizon and fault geometry for this study. We tracked faults, unconformities, growth strata, and primary seismic horizons across the grid to confirm their structural relationships. Key interpreted horizons include the Top Basement, Top Kuhlman Formation (pre-rift), Top Madbi–Meem–Lam formations (syn-rift), Top Sab'atayn Formation (late syn-rift to early post-rift),

and the major post-rift stratigraphic layers. We checked our interpretation for consistency by tying intersecting lines to available well data, following standard industry practice [15, 16].

Merging the interpreted horizons and fault surfaces let us build regional cross-sections. From there, we evaluated fault geometry, displacement trends, fault linkages, relay structures, inversion features, and flower structures. These profiles laid the groundwork for mapping the basin's history and measuring just how much the old basement fabrics influenced Jurassic rifting.

Petrel handled the seismic visualization, horizon picking, fault mapping. We drafted the maps and structural figures in ArcGIS and CorelDRAW, while Stereonet processed the orientation data [14].

Microsoft Excel and OriginPro 2024 handled the quantitative fault parameters and statistical breakdowns.

3.2. Subsurface Seismic Horizon and Fault Analysis

The seismic data reveals a subsurface dominated by high-angle, basement-involved normal faults. These structures form the basin's skeleton. They carved out the asymmetric half-graben geometry and directly controlled where sediments pooled during the Jurassic [2, 3]. Along the northwestern margin, the primary boundary faults drop the crystalline basement more than 2,800 meters to the south-southwest (Fig. 7). Because of this massive drop, the Mesozoic sedimentary succession thickens dramatically right against the master fault system.

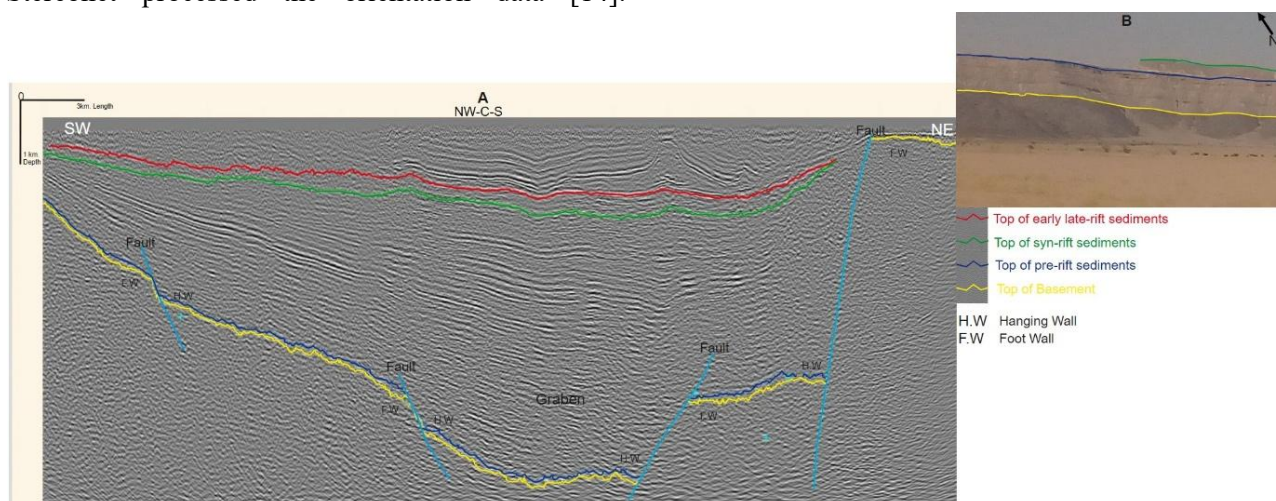


Figure 7. Representative seismic profile illustrating the basement-controlled master normal fault. The crystalline basement is downthrown by more than 2,800 m toward the south-southwest, producing an asymmetrical half-graben with progressive syn-rift thickening toward the hanging wall. (a) Seismic profile section. (b) Outcrop in real vertical and horizontal scales.

3.2.1. Basement-controlled extensional structures

Structural styles shift sharply across the basin. Profile SE-SS-1 (Fig. 8) captures a classic extensional half-graben anchored by a massive NW–SE-trending master normal fault. This single fault accommodates the bulk of the vertical displacement, dropping the

basement to the southwest. The hanging wall itself is sliced by synthetic normal faults, creating a distinct stepped geometry where fault spacing and displacement shrink as you move basin-ward. This is a textbook setup for mature continental rifts driven by progressive normal fault growth [17, 18].

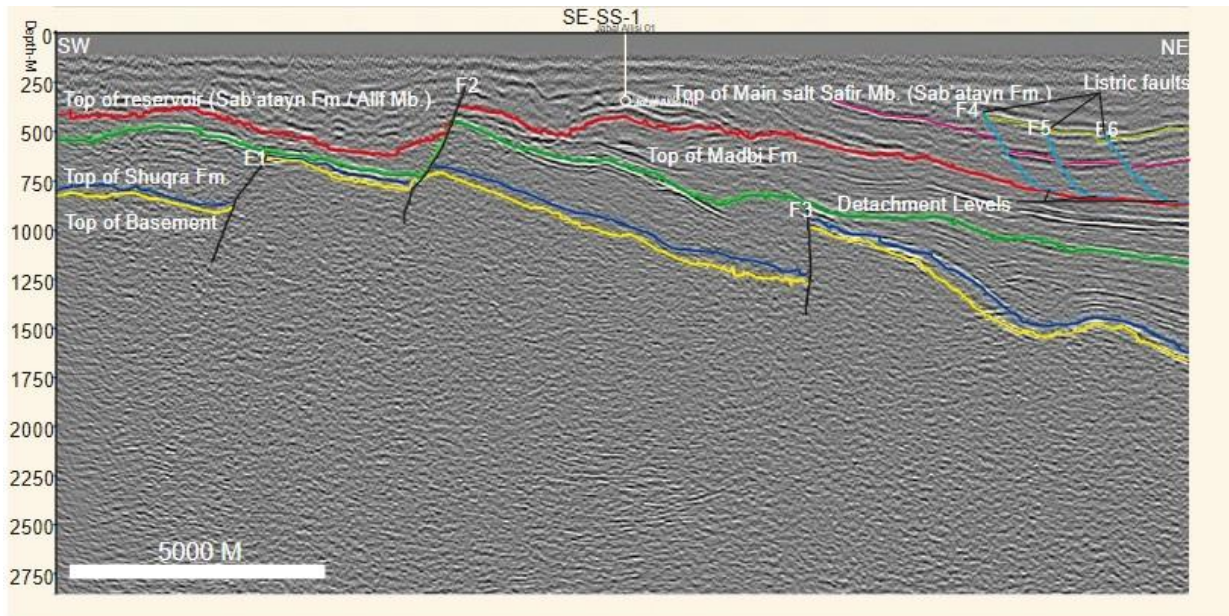


Figure 8. Interpreted seismic profile SE-SS-1 showing a basement-controlled asymmetric half-graben bounded by a major NW–SE-trending master normal fault. Progressive thickening of syn-rift strata toward the hanging wall indicates syndepositional fault activity during Jurassic extension.

Profile NW-SS-5 (Fig. 9) shows a similar extensional layout. Basement faults step the Mesozoic rocks down toward the southeast. The syn-rift units systematically swell as they approach the basin-

bounding faults. These defined growth wedges prove the faults were actively slipping while sediment filled the basin [3].

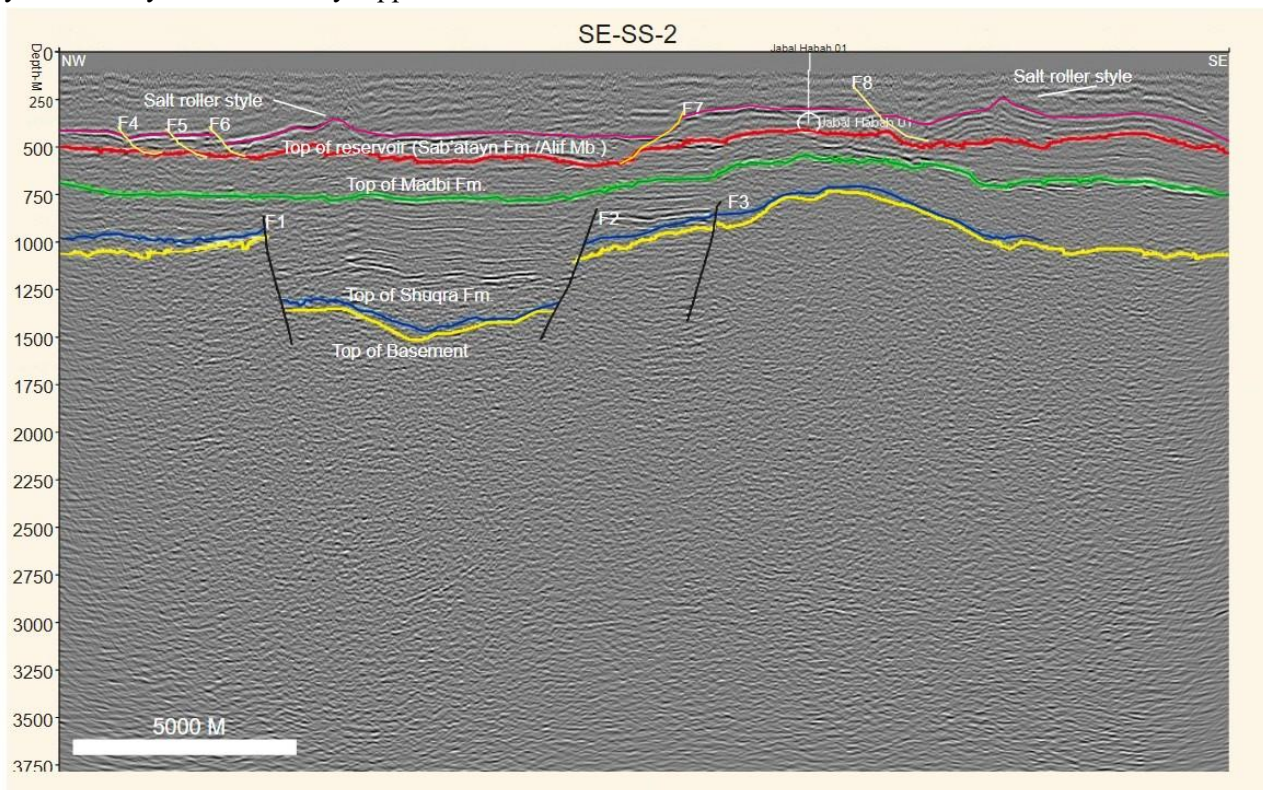


Figure 9. Interpreted seismic profile NW-SS-5 illustrating progressive basement-controlled normal faulting and syn-rift growth strata thickening toward the basin interior.

3.2.2. Detached salt tectonics

Profile SE-SS-2 (Fig. 10) tells a very different story. It exposes a shallow structural domain controlled by listric normal faults detached inside the Upper Tithonian evaporites. As these faults deepen, they flatten out and merge into the mechanically weak Safir Member evaporites. This regional detachment

surface physically isolates the upper sedimentary cover from the rigid crystalline basement beneath it. Scattered salt rollers and pillows indicate that halokinesis locally warped the extensional fault architecture, reshaping the syn-rift layers from within [19].

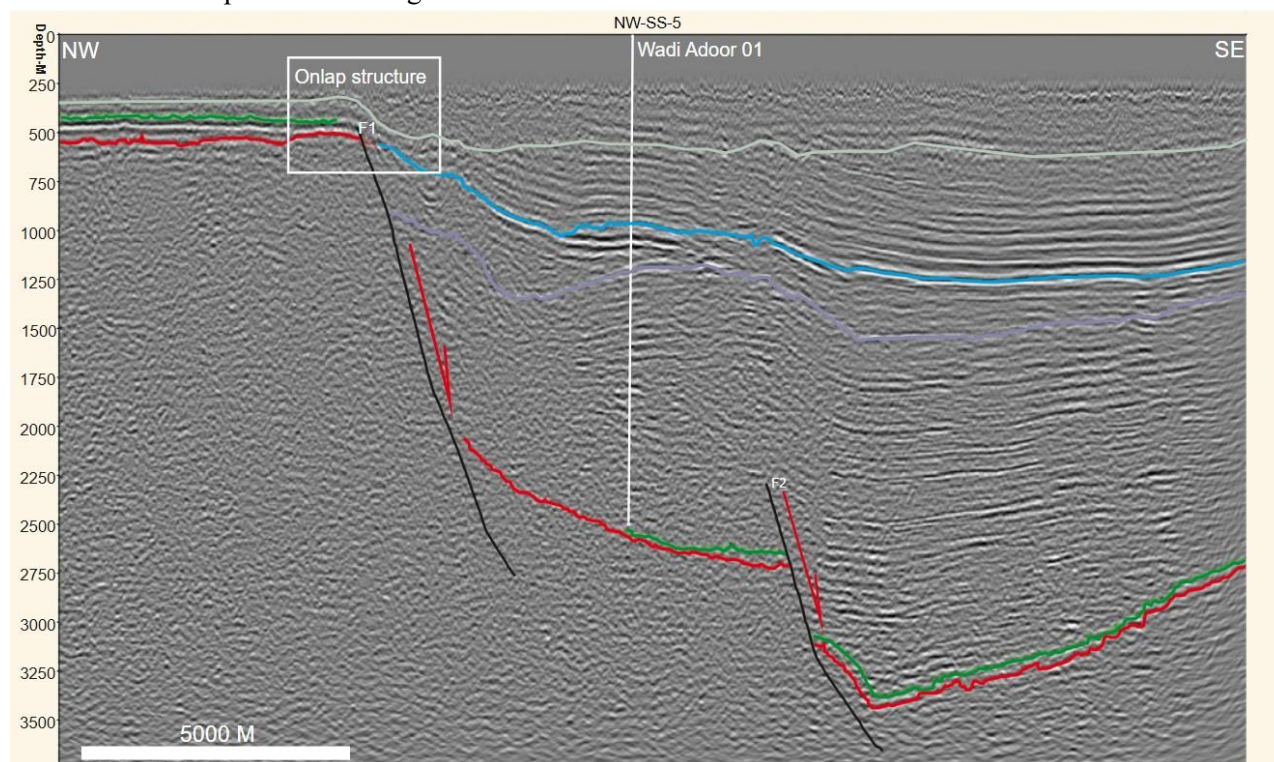


Figure 10. Seismic profile SE-SS-2 illustrating detached listric normal faults, salt rollers, and evaporite-controlled deformation within the Sab'atayn Formation.

3.2.3. Localized strike-slip reactivation

Profiles NW-SS-2 and N&NW-CS-1 uncover isolated structural snags in the northern and northeastern sectors. Here, rollover anticlines hug listric normal faults, and positive flower structures sprout from WNW–ESE-oriented fault zones. Seeing extensional and strike-slip structures side by side

suggests that strain partitioned locally. These localized positive flower structures initiated as minor transtensional adjustments during the primary Jurassic rifting phase, and were subsequently reactivated and amplified during Cenozoic tectonism [12, 20] (Figs. 11 and 12).

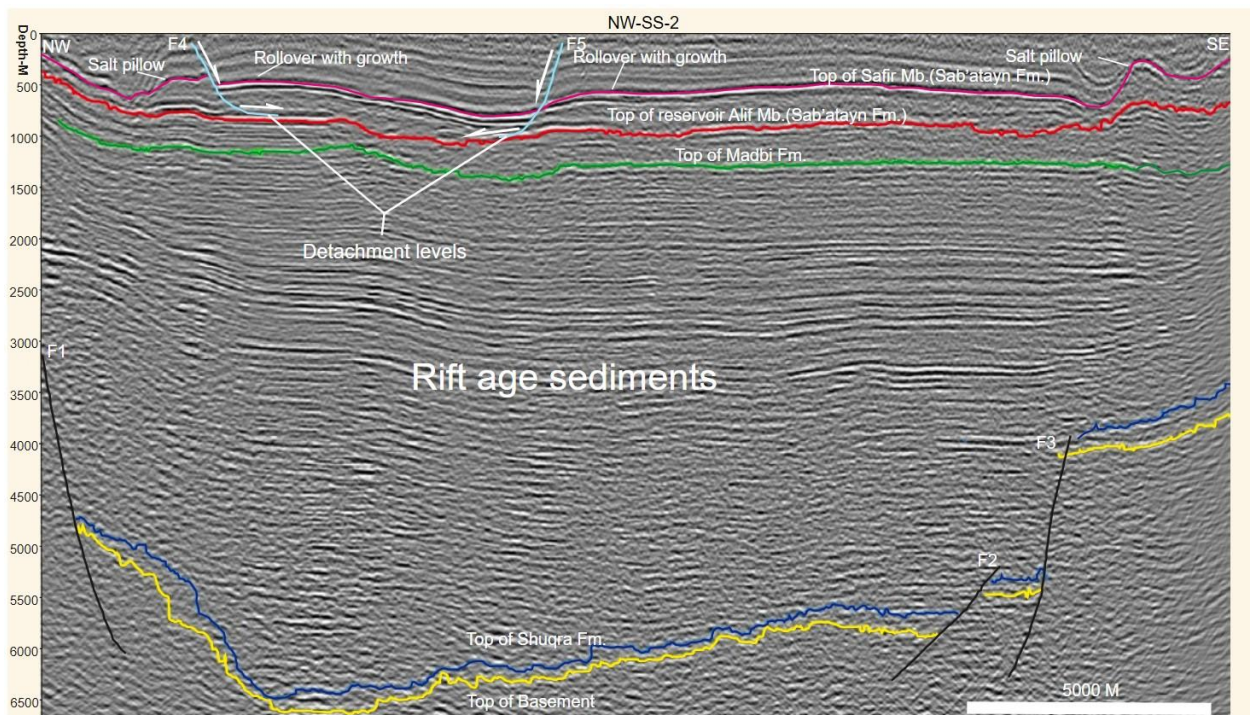


Figure 11. Interpreted seismic profile NW-SS-2 illustrating the superimposed structural architecture of the Marib Sub-basin. Deep basement-involved normal faults generated the primary half-graben geometry during Jurassic rifting, whereas shallow listric normal faults detached within the Sab'atayn evaporites produced rollover anticlines and salt pillows. The decoupling of shallow deformation from the basement demonstrates the influence of salt tectonics during the late syn-rift to post-rift evolution of the basin.

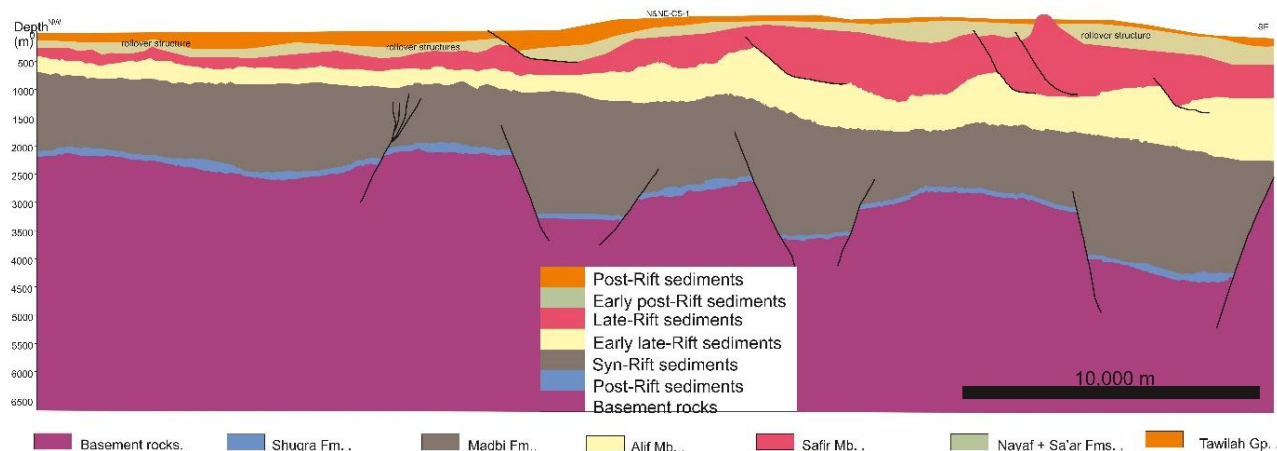


Figure 12. Seismic profiles NW-SS-2 and N&NW-CS-1 showing localized positive flower structures, rollover anticlines, and associated deformation confined to the northeastern part of the Marib Sub-basin. These structures are developed within the syn-rift succession above basement faults and record localized strike-slip reactivation superimposed on the regional extensional regime.

Looking at the dataset broadly, basement-involved normal faulting clearly drives the sub-basin's structural framework. Detached deformation rooted in the Sab'atayn evaporites simply overprints that architecture in specific spots. Meanwhile, the positive flower structures are strictly corralled in the

northeast and only appear within the syn-rift succession.

4. Results and Discussion

4.1. Discussion and Tectonic Synthesis

4.1.1. Fault Mechanics: Pull-Apart vs. Pure Extensional Regimes

Seismic profile NECSev90—running WNW-ESE (117°) from 598,313E, 1,746,699N to 635,774E, 1,728,085N—cuts right through the basin's most complex deformation. Unlike sections from the central and southwestern areas, this profile reveals localized positive flower structures buried in the Jurassic syn-rift succession, sitting directly above basement-controlled normal faults.

Steep NW-SE-trending normal faults dictate the deeper basement architecture, defining the half-graben. These faults cut deep into the crystalline rock, guiding the deposition and thickening of the syn-rift Madbi and Sab'atayn formations. Yet the flower structures above them never root into the basement. They sit entirely within the sedimentary cover. Upward-diverging fault splays warp the syn-rift sequence, while the basement underneath just displays standard extensional geometry. This strict vertical separation means the strike-slip motion was a secondary event layered over an older extensional framework. The Marib Sub-basin is, at its core, an extensional intracontinental rift.

The location of these structures is just as telling. Across the entire seismic grid, flower structures only crop up in the northeast. They are totally absent in the central or southwestern sectors, where simple basement-controlled normal faulting runs the show. Because the strike-slip deformation is so confined, it cannot possibly explain the origin of the whole basin. A pull-apart model simply does not fit the regional data.

What is fascinating is how well this localization matches the adjacent Precambrian basement. Fieldwork confirms the northeastern sector aligns perfectly with the transition zone between the Abbas Terrane and the Al-Bayda Island Arc Terrane, right against the ancient Neoproterozoic suture zone. The basement rocks here underwent intense polyphase deformation, leaving behind recumbent folds, reverse

faults, ductile shear zones, and heavy NE-SW-trending mafic dyke swarms. Those dykes run exactly parallel to the flower structures seen on seismic. At the same time, the main strike-slip structures inside the Al-Bayda Island Arc trend roughly perpendicular to them. The geometry is too clean to be a coincidence. The inherited Precambrian structural fabric heavily dictated where the later Jurassic deformation would strike.

This overlap between basement inheritance and localized strike-slip reactivation suggests flower structures formed exactly where extensional forces met mechanically scarred crust left over from the Pan-African orogeny. These structures are not the engine that built the basin. They are simply localized accommodation zones that formed during progressive extension and were later tweaked by minor strike-slip shifts.

The seismic profile also confirms the flower structures are locked inside the syn-rift interval, barely touching the post-rift succession. This timing implies strike-slip reactivation happened while Jurassic rifting was still active and extension was heavily focused along the inherited Najd structural grain. As the basin evolved, normal fault growth, regional subsidence, and salt-driven gravitational slumping took over completely, carving out the half-graben architecture we see today.

Together, the structural evidence makes a strong case: the Marib Sub-basin began as a basement-controlled extensional rift. The isolated flower structures in the northeast represent transpressional or localized transtensional adjustments triggered by old Precambrian basement fabrics. They do not point to a massive, basin-scale pull-apart system. They stay confined to the syn-rift rocks, cling to the Abbas–Al-Bayda terrane boundary, and perfectly parallel the NE-SW dyke swarms. Inherited basement flaws dictated where these structures formed, but they never fundamentally altered the basin's extensional evolution.

Geologists have argued for years about the structural engine behind the Marib Sub-basin, usually pitting

strike-slip pull-apart kinematics against pure extensional rifting. The localized flower structures on the northern and northeastern margins (Figs. 11 and 12), combined with known strike-slip fault segments near Ath Thaniyah, frequently fueled arguments for a pull-apart model driven by dextral strike-slip along WNW-ESE trends.

But when you synthesize the entire structural data grid, the primary pull-apart model falls apart. Geometric analysis shows the sub-basin's northern and southern margins are incredibly symmetrical, holding a steady NW–SE orientation for miles. Plotting every compiled normal fault plane on a stereonet reveals a highly organized structural system. The dominant fault sets lock in strictly parallel to the master basin margins along a clean NW-SE axis. There are no

major, through-going strike-slip fault zones visible on seismic or at the surface. If pull-apart strike-slip

translation built this basin, those faults would have to be there to make the kinematics work. They aren't.

As a result, we classify the Marib Sub-basin as a predominantly extensional rift basin. The flower geometries and trace strike-slip components are minor internal accommodations. A pair of regional normal fault arrays drove the system: a primary set striking NW-SE, supported by a secondary set striking SW-NE.

Unlike the messy localized flower structures in the northeast (Figs. 11 and 12), nearly every other seismic profile displays clean, simple basement-controlled half-grabens defined by high-angle normal faults and syn-rift growth strata (e.g., Fig. 13). This widespread extensional layout proves strike-slip deformation was a local quirk, not a basin-scale driver.

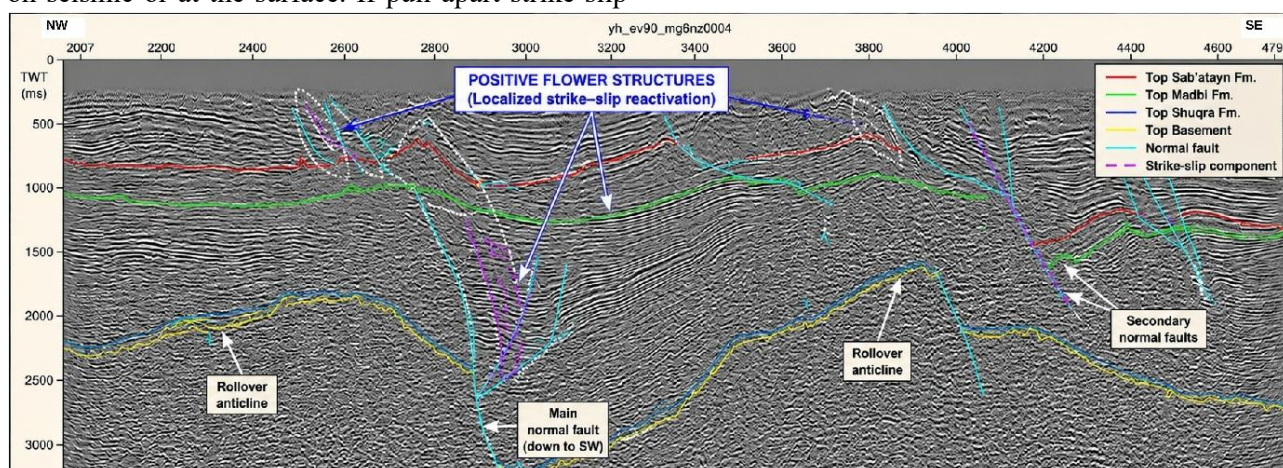


Figure 13. Interpreted seismic profile (NECSev90) showing a basement-controlled half-graben bounded by a major normal fault (F1). A localized positive flower structure is developed within the syn-rift succession above the master fault, producing gentle uplift of the Jurassic horizons. The structure is restricted to the sedimentary cover and is interpreted as a localized strike-slip reactivation superimposed on the regional extensional architecture rather than evidence for basin-scale pull-apart tectonics.

The seismic sections do show steep basement-rooted faults waking up under transpression, pushing positive flower structures up into the syn-rift sequence. But the actual sense of strike-slip motion must be pinned down using integrated geological and structural field evidence, rather than inferred blindly from a cross-sectional geometry.

4.1.2. Geometric Style and Structural Superimposition

Two superimposed structural tiers define the basin's architecture. The deeper tier is built on basement-involved, high-angle normal faults that map out the primary half-graben. The shallow tier consists of detached listric normal faults and salt-related structures floating in the sedimentary cover.

This shallow tier completely ignores the basement. Detached listric normal faults and active salt tectonics run the show. Multiple detachment levels—sitting at the base of the Alif Member, inside the main Sab'atayn halites, and near the top of the Naifa/Sa'ar Formations—mechanically isolate this shallow network from the deep rocks. Massive low-side rollover anticlines and salt rollers pile up directly on top of rigid basement blocks. You can see this two-tiered deformation style perfectly preserved across the southeastern and northeastern sectors.

The sub-basin also splinters significantly along its strike. Walk the length of the basin, and the geometry of individual half-grabens abruptly shifts every 20 to 50 kilometers. 'Dog-leg' fault bends, bifurcations, en echelon stepping, and anastomosing fault zones chop the basin into pieces. This structural chaos created isolated 'trap-door' sub-basins and enclosed structural channels at the top of the Madbi Formation. It is clear proof the basin endured intense longitudinal and transverse segmentation while it was actively growing (Fig. 14).

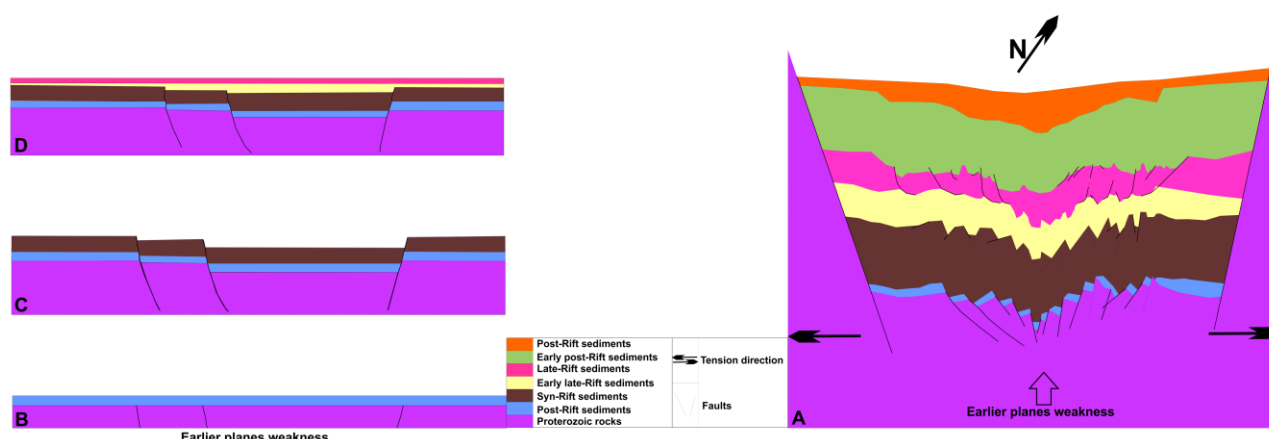


Figure 14. Conceptual models illustrating the structural superimposition and geometric evolution of the Marib Sub-basin. (a) Structural superimposition model; (b) pre-rift stage; (c) syn-rift stage; and (d) post-rift stage.

4.1.3. Chronological Evolution and Deformational Timeline

By matching surface outcrops to subsurface seismic growth packages, we can trace the structural

evolution through four distinct stages (Table 1; Fig. 15).

Table 1. Proposed tectono-stratigraphic framework for the Marib Sub-basin, integrating tectonic stages, stratigraphic targets, and the characteristic deformation styles and kinematic indicators that document basin evolution from the Oxfordian to the present.

Tectonic Stage	Stratigraphic Target	Deformational Characteristics & Kinematic Indicators
1. Early-Rift Sag Phase Callovian to Oxfordian	Kuhlan Fm. to Lower Shuqra Fm.	Gentle, regionally uniform basin-ward thickening. Minor faulting with minimal throws. Represents initial crustal stretching and broad lithospheric subsidence before localized faulting.
2. Main Rift Phase (Kimmeridgian to Tithonian)	Mid-Madbi Fm. (Meem/Lam) to Alif Mb.	Concentrated high-angle normal faulting along discrete Najd weak zones. Marked tilting of half-grabens, dramatic growth-strata thickening into sub-basin deeps (2-3x thickness in hanging walls vs. footwalls), and distinct structural onlaps.
3. Late-Rift to Sag Transition (Late Tithonian to Cretaceous)	Sab'atayn Fm. (Salt) to Tawilah Group	Decline of active basement stretching; transition to regional thermal subsidence. Initiation of gravity-driven detached listric faulting and halite flowage triggered by differential sedimentary loading. Salt evacuated basin deeps to form pillows over basement highs.

Tectonic Stage	Stratigraphic Target	Deformational Characteristics & Kinematic Indicators
4. Cenozoic Overprint & Reactivation (Oligocene to Recent)	Tawilah Group to Quaternary Cover	Opening of the Red Sea and Gulf of Aden rifts. Induced strong regional northeastward tilting ($\sim 1^\circ$ to 10° NE). Reactivated ancient Jurassic faults, triggering modern Quaternary landslide slumps, fault scarps, and basaltic fissure volcanism.

The deformation history etched into the Marib Sub-basin proves inherited Precambrian basement fabrics fundamentally dictated where and how Mesozoic rift faults formed, grew, and eventually reactivated. We should expect to find similar structural inheritance across the rest of the western Sab'atayn Basin and in other intracontinental rifts scattered across the southern Arabian Plate.

4.2. Additive Knowledge and Regional Implications

While previous studies in the Marib Sub-basin have predominantly focused on petroleum systems and stratigraphy, this study adds significant new knowledge by providing a continuous, basin-wide structural synthesis. By quantifying the massive basement downthrow ($>2,800$ m) and proving that flower structures are merely localized phenomena restricted to the northeastern syn-rift succession, this

research fundamentally shifts the regional tectonic paradigm from a pull-apart model to an extension-dominated framework.

4.3. Uncertainties and Limitations

To validate these interpretations, several limitations must be acknowledged. The reliance on 2D seismic reflection data inherently limits the spatial resolution of structural mapping compared to 3D seismic volumes, introducing some interpretative uncertainty regarding the lateral continuity of minor faults. Additionally, the precise geometry of the deep crystalline basement beneath thick evaporite deposits may be partially obscured by signal attenuation. Finally, localized surface expressions have undergone Cenozoic uplift, requiring cautious extrapolation when integrating surface and subsurface datasets.

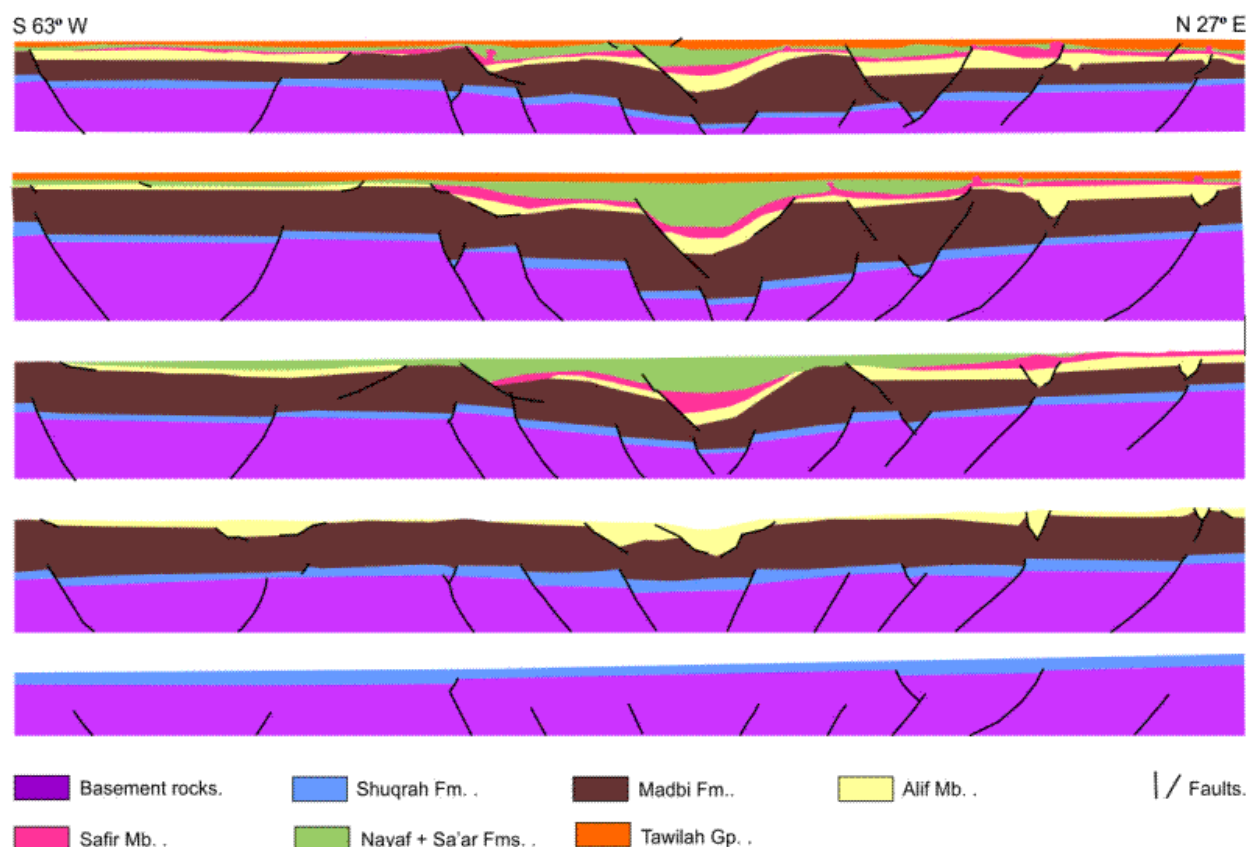


Figure 15. Conceptual model illustrating the chronological tectonic evolution of the Marib Sub-basin from pre-rift inheritance through Jurassic rifting, post-rift thermal subsidence, salt-controlled deformation, and Cenozoic tectonic reactivation.

5. Conclusions

Based on the integration of detailed field geological mapping and 2D seismic reflection data, the structural evolution of the Marib Sub-basin can be summarized in the following key points:

1. The Marib Sub-basin is fundamentally an asymmetric, NW–SE-trending half-graben driven by Jurassic extension, structurally refuting models that suggest a basin-scale pull-apart origin.
2. Basin geometry and fault localization were strongly dictated by inherited Precambrian basement architecture, specifically the Najd Fault System and the boundary between the Abbas Gneiss and Al-Bayda Island Arc terranes.
3. The structural framework is defined by a two-tiered deformational style: deep, high-angle basement-rooted normal faults that control massive syn-rift subsidence (downthrowing the basement >2,800 m), and a shallow, mechanically detached system of listric faults and salt structures within the Sab'atayn evaporites.
4. Positive flower structures are isolated features confined entirely to the syn-rift succession in the northeastern sector, representing localized transtensional adjustments rather than regional strike-slip kinematics.
5. The basin evolved through four distinct tectonic stages: initial pre-rift broad crustal sagging, main Jurassic syn-rift extension, late-rift thermal subsidence with halokinesis, and final localized reactivation during Cenozoic tectonism.

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Author Contributions

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Conflict of Interest Disclosure

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.

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