

STRUCTURAL INTERPRETATION OF THE MIDYAN
PENINSULA USING NEWLY ACQUIRED 2D SEISMIC
LINES AND OUTCROP DATA

BY

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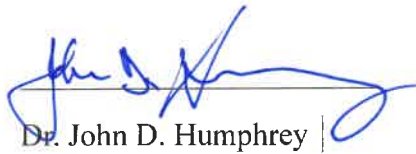
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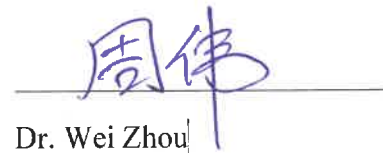
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[Dedication]

To my parents, their encouragement has always driven me forward. And to my wife and two daughters, their love and patience has carried me through every challenge

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I would like to express my deepest gratitude to my advisor, Dr. Abdullatif Al-Shuhail, for his/her invaluable guidance, support, and encouragement throughout the course of this research. His/her insights and mentorship were instrumental in shaping the direction and depth of this work.

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ABSTRACT

Full Name : Ahmed Alhani

Thesis Title : STRUCTURAL INTERPRETATION OF THE MIDYAN
PENINSULA USING NEWLY ACQUIRED 2D SEISMIC LINES
AND OUTCROP DATA

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The Midyan peninsula located in NW Saudi has a complicated geological history. With a combination of major unconformities, salt movements, and different faulting regimes. Numerous studies over the past few decades have examined this basin but only few of them have used a multi-disciplinary approach to appropriately address the complexities of this basin. This study integrates newly acquired seismic, outcrop, and magnetic data to analyze micro- and macro-scale variables which have led to the creation, infill, and deformation of this basin.

I will relate the structure in the Midyan basin to the structures in Gulf of Suez and propose a model for the structural evolution of the area by integrating seismic interpretation, and outcrop data. This integrated approach will present a new comprehensive model that links the structures in the area, and explains the regional geology to fit the existing structural trends.

ملخص الرسالة

الاسم الكامل: أحمد حاتم ال هاني

عنوان الرسالة: التفسير الهيكلي لشبه جزيرة مدين بالاستناد إلى خطوط سيزمية ثنائية الأبعاد مكتسبة حديثاً وبيانات
النتوءات الجيولوجية السطحية

التخصص: جيوفيزياء

تاريخ الدرجة العلمية: ديسمبر 2024

تقع شبه جزيرة مدين في شمال غرب المملكة العربية السعودية، وتتمتع بتاريخ جيولوجي معقد، نتيجة لتداخل عدد من التكوينات الصخرية الكبرى، وترسبات الملح، واختلاف ترابط الصدوع. لقد ناقشت العديد من الدراسات هذا الحوض خلال العقود الماضية، إلا أن قلة منها اعتمدت على منهجية متعددة التخصصات لمعالجة تعقيداته بشكل مناسب. تدمج هذه الدراسة بيانات سيزمية حديثة مع بيانات النتوءات الجيولوجية السطحية والبيانات المغناطيسية لتحليل المتغيرات على المستويين الدقيق والواسع، والتي أسهمت في تكوين هذا الحوض وملئه وتشويهه البنيوي.

سأقوم بربط التركيب الجيولوجي في حوض مدين بالطبقات والتركيبات الموجودة في خليج السويس، واقتراح نموذج للتطور الهيكلي للمنطقة من خلال دمج تفسير البيانات السيزمية مع بيانات النتوءات السطحية. وسيوفر هذا النهج المتكامل نموذجاً شاملاً جديداً يربط بين الطبقات الجيولوجية المختلفة ويشرح الجيولوجيا الإقليمية بما يتماشى مع الاتجاهات الهيكلية القائمة.

CHAPTER 1

INTRODUCTION

The cretaceous formations in the Gulf of Suez and the Midyan basin are around 83.4 Million years old, and they record the earliest deposition in the basin. The Red Sea rift has started between 33-28 Ma where the rift was initiated as a series of half grabens that then organized to form the basin bounding faults that organized as the edge of the basin I see today at the coast line. Around 11-12 Ma the initiation of Sea floor spreading in the south with a rotation in the plate tectonics that brought with it the initiation of the strike slip motion in the Red Sea rift, and started to isolate the motion in the north to abandon Gulf of Suez. Around 5 Ma, while organized seafloor spreading occurred in the southern Red Sea, the strike-slip displacement started to focus in the Gulf of Aqaba. In the middle of all this sequence, the Mansiyah salt was deposited all over the Red Sea sometime between 15-11 Ma during a salinity crisis (Figure2). These three major influences on the current day structure (rift, salt, and strike slip tectonics) are superimposed on the existing formation today in the Midyan Peninsula. Carefully dis-entangling the effects on the geology will decipher the geologic history and depositional environment of the basin and gives a better understanding for the geologic system in the area.

With the newly acquired 2D seismic depth lines in the Midyan field, this study requires the integration of a comprehensive regional understanding and incorporating different geophysical methods to get the regional story, as well as well as incorporating the work done on the Gulf of Suez with that done on Gulf of Aqaba, and the Red Sea. I will also incorporate the outcrop

information to attempt to correlate the lithology and its structural indications. Using published spreading rates and angles from studying the magnetic anomalies of the sea floor spreading the southern Red Sea, magnetic profiles on the Midyan peninsula, published on shore and offshore seismic lines, and outcrop faults from field visits, and satellite images, will build a comprehensive structural framework to incorporate all observations, and link with published structural maps from the Gulf of Suez.



Figure 1. Red Sea Landsat image (<https://maps.google.com>).

GEOLOGICAL COLUMN – MIDYAN AREA

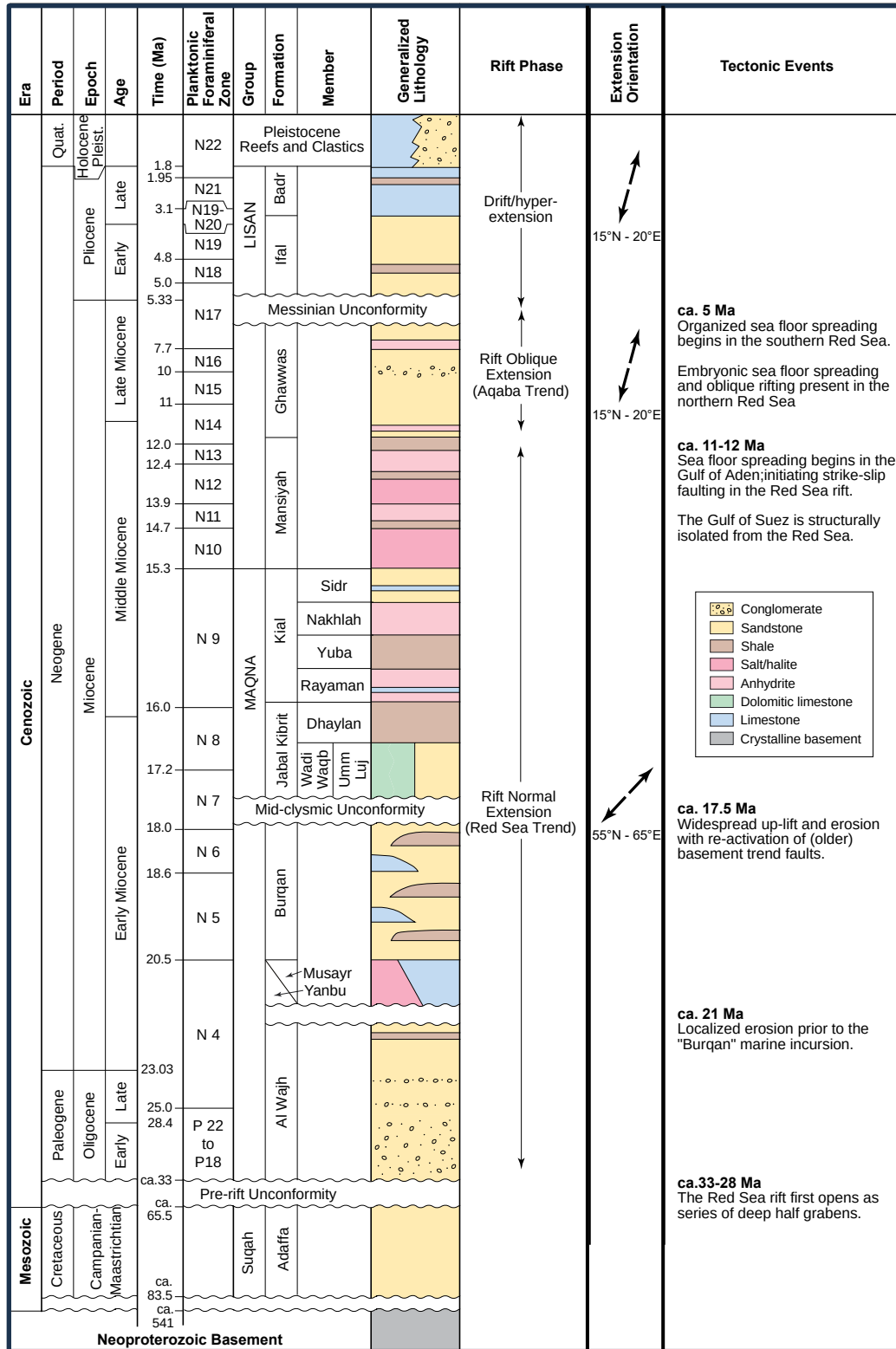


Figure 2. Generalized lithostratigraphy of the Midyan Peninsula (based on Hughes and Johnson, 2005) showing major tectonic events

1.1 Chapter outlines and objectives

1.1.1 Literature Review

This chapter will summarize previous studies on the Red Sea and Gulf of Aqaba regions, with a focus on rift dynamics, salt tectonics, and strike-slip faulting. It will explore the regional geology and stratigraphy, synthesizing existing interpretations to identify knowledge gaps addressed in this study.

1.1.2 Methodology

This chapter will detail the multidisciplinary approach taken in the study:

- Picking and verifying faults using satellite imagery and field mapping.
- Interpreting seismic data to delineate structural features and lithological units.
- Conducting basin restorations to reconstruct tectonic evolution and identify accommodation zones.

1.1.3 Results

This chapter will present the findings of the research:

- Identified fault trends and their implications for rift and strike-slip tectonics.
- Evidence of salt evacuation and its impact on overlying strata.
- Structural models developed through seismic and satellite data integration.
- Insights into the regional polarity flip and its role in accommodation zones.

1.1.4 Discussion

This chapter will interpret the results in the context of regional tectonics:

- The role of the Midyan area as a transition zone between the Red Sea rift and Gulf of Aqaba strike-slip system.
- The implications of identified structures for the basin's tectonostratigraphic evolution.
- Comparisons with analogous features in the Gulf of Suez.

1.1.5 Conclusion

This chapter will synthesize the study's key findings, emphasizing the structural evolution of the Midyan Peninsula. It will also highlight the study's contributions to understanding Red Sea tectonics and propose directions for future research.

1.2 Statement of problem

A comprehensive structural model for the Midyan Peninsula in the northern Red Sea has not been addressed in detail in the literature. The literature contains enough data points, but with sometimes contradicting interpretations, and incorporates it with lithology. An integrated study to demonstrate the model using multiple data points linking it with the lithology and incorporating desktop and field geology would present a great addition to the existing knowledge.

1.3 Research objective

Newly acquired 2D seismic lines by the NEOM team in the Midyan peninsula offer a unique opportunity to link the wide range of publicly available data that exists in literature and create a complete structural model of the Midyan peninsula. This data needs to be incorporated together to explain all existing observations that, at times, appear to contradict one another.

In this study, I will use this seismic to address the complicated history of the Midyan basin. I will use published spread rates to build a plate scale restoration to link the structure to the Gulf of Suez. I will link it to specific sub-regional structural trends. I will drive our understanding from mapped outcrop structures and lithologies. I will also use lithological variations to guide our understanding of the structural evolution through time. All of this will provide a comprehensive model for the tectonostratigraphy of the Midyan basin. |

CHAPTER 2

LITERATURE REVIEW

2.1 Regional Geology

Situated in the northwestern part of Saudi Arabia, the area of interest lies directly northeast of the Red Sea Basin, which is a divergent plate boundary. This basin, that started as a continental rift around 30-32 million years ago, was triggered by the emergence of the Afar Plume (Figure 3-a and -b) (Delaunay, et al., 2023) that through time developed to become an oceanic rift that now bounds the African and Arabian plates. The rift is postulated to have simultaneously started and extends all the way from the south of the Red Sea, all the way to the north of the Gulf of Suez as one system. The rift initially propagated as an asymmetric rift, expanding from south to north through a sequence of deep half graben zones dipping primarily either towards the Arabian, or the African side. Accommodation between polarity zones link through oblique cross-basinal arches.

Formations from the Pre-Miocene predate the rift's formation. Of these, the Cretaceous formations are the oldest, showing considerable thickness in the Gulf of Suez and gradually thinning southward until they vanish both offshore and in outcrops on the Saudi Arabian side in the northern Red Sea regions, as observed in the Adaffa and Usfan Formations (Hughes, 2005). Notably, some Cretaceous outcrops, such as the Adaffa Sandstone Formation, remain preserved within down-dropped basin grabens in the Midyan area. Additional Cretaceous outcrops are found within grabens along the Saudi coast, extending almost to the Yemen border.

The early phase of the rift involved rift-normal extension, hypothesized to have simultaneously opened the entire 2,200 km length of the Red Sea (Bosworth, 2015). This stage included the deposition of the Early Oligocene Al Wajh formation, characterized by continental sands prevalent throughout the Red Sea as continental red beds and lacustrine deposits, reaching up to 2200 m thick. A subsequent marine incursion led to the deposition of deep marine turbidites of the Burqan formation in tectonically active areas, where this formation is notably thick.

A notable shift in the depositional environment is evidenced by outcrops that display the mid-clysmic unconformity, dating back to approximately 17.5-18 million years ago, marking the end of the Burqan deposition (Tubbs et al, 2014). The Maqna group reflects a period of low tectonic activity and basin-wide restriction, characterized by the deposition of several regional anhydrite formations interlaid with clastic and carbonate formations. This period led to a basin-wide salinity crisis, resulting in the deposition of the extensive Mansiyah halite.

Between 14-12 million years ago, the Gulf of Aden got initiated coinciding with the collision of the Arabian and Eurasian plates. This event caused a counterclockwise rotation of the Arabian plate around a north-African Euler pole, altering the Red Sea's extension to a rift-oblique orientation (Bosworth, 2015). This change reactivated certain faults, leading to strike-slip deformation to accommodate the differential extension. This also coincided with the initiation of the onset of oceanic rift in the south of the Red Sea.

The formation of the Gulf of Aqaba facilitated the plate rotation, leading to the abandonment of extension along the Gulf of Suez, rendering it a 'dead' rift. This period also saw significant late strike-slip deformation across the basin, particularly in the northern Red Sea and within the Midyan peninsula, with most changes occurring offshore. The resulting subsalt topographical shifts drove the Mansiyah halite towards those local highs, creating accommodation zones filled by the post-salt Ghawwas and Lisan formations (abd el-naby, abd el-aal, kuss, boukhary, & aref, 2009). Evidence of this salt movement, or diapirism, is evident in the topography, including salt collapse features along the coastline, modern-day reefs as evacuation structures, and circular collapses throughout the Red Sea.

Approximately 5 million years ago, seafloor spreading commenced in the southern Red Sea, establishing an organized ridge that shifted most deformation to the sea's center. Consequently, continental rifting ceased in the south, with only localized offshore deformation continuing in the north. The Red Sea transitioned into a drift regime, localizing extension to its center while movement occurred along the Aqaba strike-slip system, resulting in a total left-lateral displacement of 107 km. The southern end of the Red Sea additionally opened by 26 km due to plate rotation. This displacement led to the development of several pull-apart basins along transtensional bends, with the Gulf of Aqaba Sea forming a significant pull-apart basin separating the Sinai Peninsula from the Midyan area (Tubbs, et al., 2014).

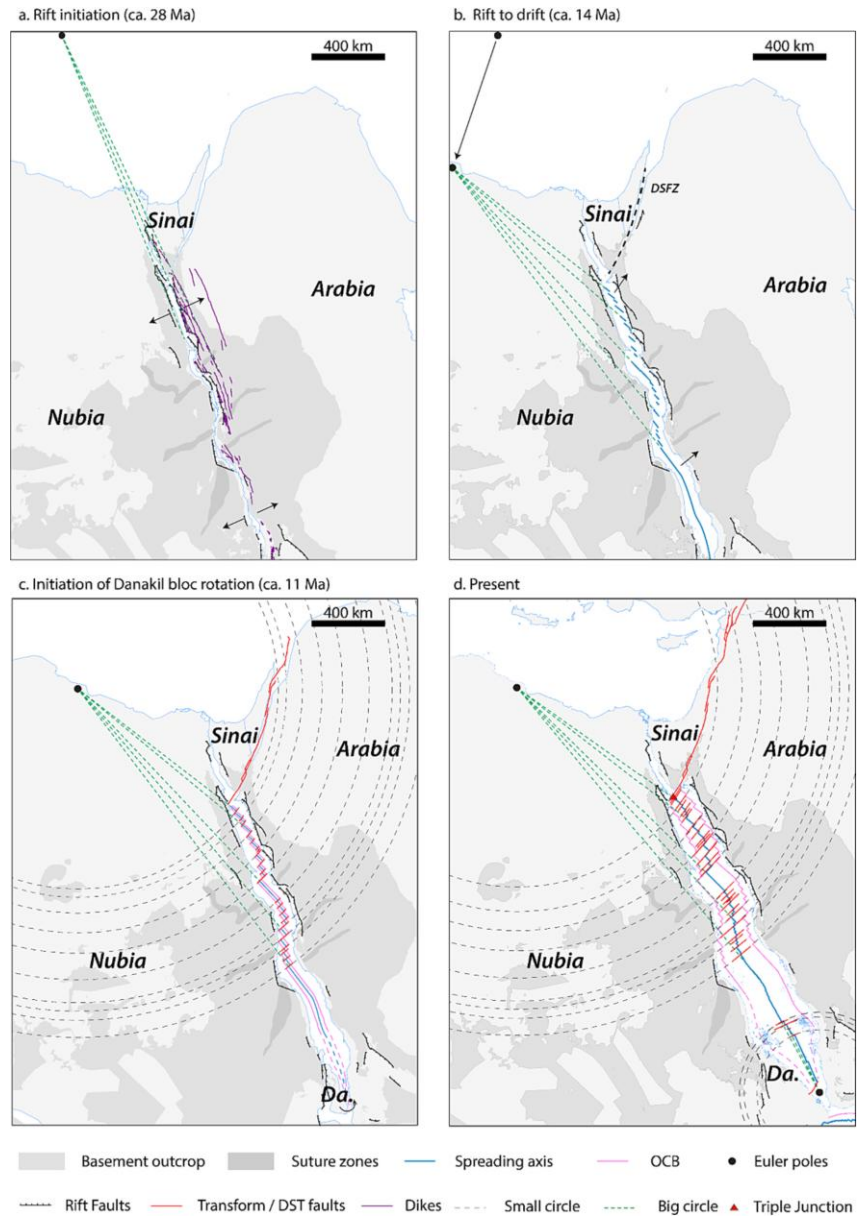


Figure 3. The evolution of the Red Sea rift from the initiation of the Afar plume, through the rift climax, strike slip initiation and rotation axis change, and to modern day system. (Delaunay, 2023)

2.2 Structural Settings

Developing as an Asymmetric rift, the Red Sea had undergone oblique extension starting from the Oligocene through to the Late Miocene. Half grabens form usually in zones of alternating polarities with oblique accommodation zones. This is evidenced in the lab from sandbox experiments as in

figure 4a. (abd el-naby, abd el-aal, kuss, boukhary, & aref, 2009) We can see that under transtensional strain, the geometry bound by synthetic faults formed across the width of the basin. The Red transfer or accommodation zones represent a displacement link across the different polarity zone to rotate the dip direction and create space accommodation across the east and west dipping slips. This is apparent in Gulf of Suez maps (figure 4b) (Bosworth, 2015) and indications of it can be seen in the Red Sea, as well. Understanding the regional context and half graben regional polarity helps us better extrapolate geologic interpretation and de-risk models .

Moreover, the faulting present in pre-rift formation outcrops within this region reveals a history of episodic reactivation that occurred during the rifting process of the Red Sea basin. These reactivations are critical in deciphering the geological history and evolution of the area (abd el-wahed, ashmawy, & tawfik, 2010) .

The mapping of these accommodation zones is not just an academic exercise; it has practical implications. It helps in identifying intra-basinal highs and lows within the different grabens, elucidating how each fault zone is interconnected with the next. Such mappings provide essential guidance for regional geological interpretation and are invaluable for conducting potential field surveys in areas like the Midyan (coffield & schamel, 1989) (griffin, 1999).

Understanding these geological structures and their relationships offers a comprehensive guide to the regional geology of the area. It is particularly beneficial for exploration and development

activities, as it provides insights into the subsurface characteristics of the region, enhancing our ability to make informed decisions regarding resource exploration and environmental management.

2.3 Stratigraphic Framework

The stratigraphy of the Red Sea basin is intrinsically linked to its tectonic evolution, particularly the development of the Red Sea rift. This relationship has significant implications for the characterization of the geological layers in the region. Notably, the pre-rift strata tend to be relatively thin, often directly overlaying the crystalline basement rock. Consequently, the stratigraphic framework is best understood in the context of the different stages of rifting: pre-rift, syn-rift, late rift, and post-rift. Each of these stages reflects the influence of the rift's kinematics on the depositional environment, basin morphology, and available space for sediment accumulation (Bosworth, 2015) (Hughes & Johnson, 2005) (Tubbs, et al., 2014).

In the context of the Red Sea, it is crucial to consider the spatial creation within the various zones and the cessation of activity along the rift margin faults. Currently, plate motion is accommodated primarily by space creation offshore. Several theories exist regarding the onset of oceanic crust formation and the hyper-extension of the continental crust in offshore areas. This report defines the rift formation based on the kinematics of rift faults found onshore. Insights into the onshore basin have been augmented by published literature on drilling results and outcrop studies.

A key regional event is a basin-wide salinity crisis, leading to the deposition of a substantial halite section known as the Mansiyah. This salt section is easily identified in oil exploration and development wells. Its absence is typically indicated by classic salt evacuation structures and weld surfaces. The deposition of the Mansiyah, which occurred in the drift phase of the rift, and as such is classified to be “post rift” as associated with onshore rift faults and serves as a distinct marker within the sedimentary section.

The stratigraphy in the areas of interest has been categorized into major groups and formations, as detailed in studies by Tubbs et al (2015) and Hughes and Johnson (2005). For the purposes of this report, the following formations/groups are of particular relevance and significance for general activities:

1. Al Wajh Formation: Represents the earliest phase of rift deposition, characterized by continental red beds forming sand wedges atop the basement, primarily within rotated half grabens. The Al Wajh sediments are expected to consist mainly of high porosity sandstone, interspersed with layers of tight facies in shales deposited along lacustrine beds within the basin.
2. Burqan Formation: Signifies the initial marine incursion that spanned the basin. This phase marks the organized propagation of the rift across the Red Sea basin, connecting with global oceans. The Burqan Formation predominantly comprises marine turbidites, typically featuring interbedded sandstones and mudstones/shales. These create vertically stacked reservoir-seal pairs, crucial for hydrocarbon exploration.
3. Maqna Group: During this phase, the rift's kinematics begin to slow, evident onshore. The group is characterized by formations of siliciclastic/carbonate layers and anhydrites, indicating basin-

wide restrictions. The Maqna Group includes vertically stacked reservoir-seal pairs with two internal anhydrite formation seals.

4. Mansiyah Formation: This massive halite layer, though its age is not precisely determined, signifies the climax of basin-wide restriction and a period of slow subsidence. Its formation is correlated to the cessation of active rifting along the Red Sea faults. The Mansiyah salt serves as the final regional seal in the area, capping the Maqna Group. However, this deposit is locally breached by rift faults that offset the base of the salt by a thickness greater than the remaining salt atop that fault.

5. Ghawwas Formation: This post-salt formation is significantly influenced by salt evacuation, which controls both the accommodation space and the formation structures. It's mostly clastic and represents most of the outcrop planes around the Midyan area.

When creating a subsurface model from seismic sections for drilling prognosis, the stratigraphy is categorized in a manner that informs drilling planning and decision-making. The stratigraphic section is thus divided based on general drilling hazards and seismic markers, resulting in four main sections: Basement, Pre-Salt, Salt, and Post-Salt.

- Basement Section: Comprised of crystalline rocks. The sedimentary formations overlying the basement may be weathered and fractured. Identifying the basement's top in seismic sections involves picking the deepest coherent faulted reflector, usually tied to an outcrop basement pick.

- Pre-Salt Section: This includes the pre-rift and rift sections, encompassing the Maqna, Burqan, and Al Wajh formations. Given the rudimentary understanding of specific lithology in the rift section, grouping these formations simplifies the analysis. The thickness of these formations is variable and basin-dependent, making it challenging to predict different boundaries within the pre-

salt formations. Special attention is required when drilling through the Maqna's interbedded anhydrite seal.

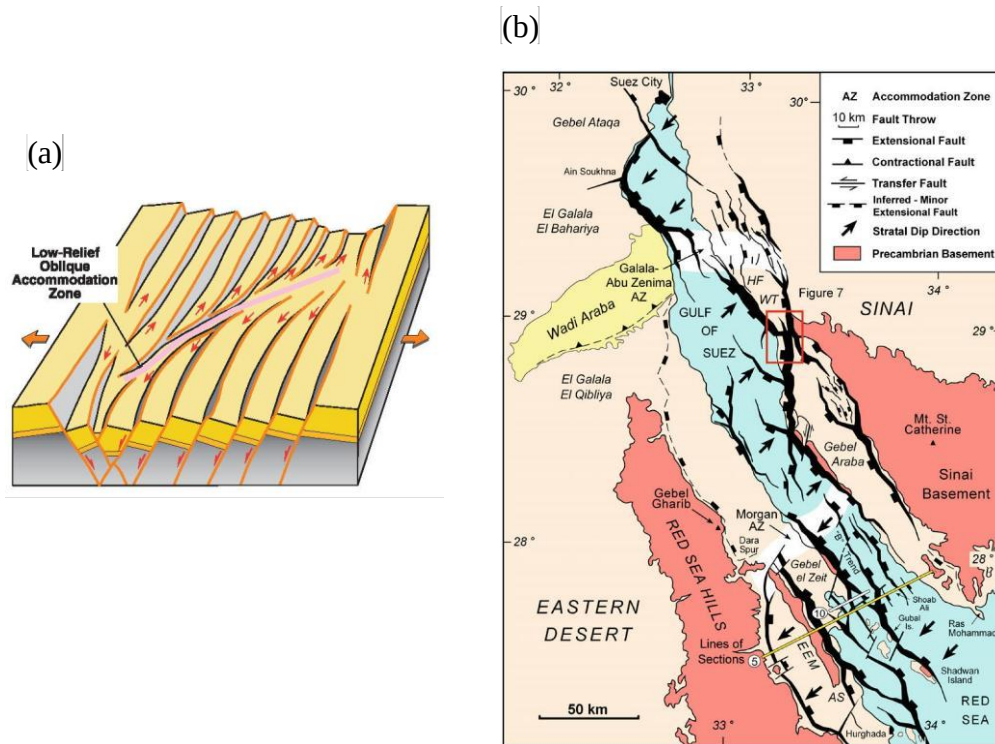


Figure 4 (a) Schematic of the transfer zone in asymmetric fault system from sandbox experiment. (McClay, 2002) (b) Faults in Gulf of Suez with different transfer zones labelled. (Bosworth, 2005)

CHAPTER 3

Methodology

3.1 Picking Outcrop Faults

3.1.1 Fault Types

Strike-Slip Faults

Strike-slip faults were identified using high-resolution satellite imagery, focusing on lateral displacements of geomorphic and stratigraphic features. Characteristic indicators include linear alignments, en echelon fractures, and offset streams or valleys. This approach follows techniques for remote fault identification outlined by Blenkinsop (2000), who emphasizes the utility of satellite imagery in capturing regional fault geometries and kinematics

Rift Faults

The whole Red Sea is an extensional basin, and the faults have been extensively studied, and published. It's well understood that the coast line across the red sea is an uplifted rift shoulder. Rift faults were mapped by identifying extensional features typical of rifted basins, including fault scarps, horsts, and grabens. These features, aligned with regional extensional stresses, were confirmed based on criteria described by Morley (2002), who provides comprehensive guidelines for interpreting rift basin structures on satellite imagery.

3.1.2 Confirming Satellite Interpretation with Field Mapping

Confirming Strike-Slip Faults

Field mapping was conducted to verify the characteristics and orientations of strike-slip faults identified in satellite imagery. Observations included slickensides, fault gouges, and sub-vertical beds exposed fault planes. In-field fault verification techniques are adapted from the work of Angelier (1994), which emphasizes fault surface mapping for validating satellite-based interpretations.

Confirming rift faults

In the field, rift faults were confirmed by examining outcrop relationships and the orientation of fault scarps. This process relied on methodologies by Morley (2007), who describes how to recognize extensional faulting through field indicators like hanging wall collapse and footwall uplift .

Age Dating Faults

Age constraints on faulting were established by identifying syn-kinematic and post-kinematic sedimentary layers in the stratigraphy adjacent to fault planes. Syn-kinematic deposits that terminate against fault planes were used for age dating, with overlying post-kinematic layers marking the cessation of faulting. This approach follows techniques from McClay (1991), who outlines methods for using sedimentary sequences to constrain fault timing based on structural geometry.

3.2 Seismic Interpretation

3.2.1 Seismic Reflection Surveys

Seismic reflections are caused by changes in the acoustic impedance of the ground. The boundary between different layers in the ground creates a change in acoustic impedance through the boundary that causes the downward propagating wavefront to split into a downward and upward propagation. The upward traveling wave is called a reflection, and creates an image of the subsurface once recorded on the surface.

3.2.2 Horizon Interpretation

When picking seismic reflections, continuous seismic horizons represent ground layers. Identifying the specific formations can be done by several methods. The most robust method is conventionally a seismic-well tie using VSP. In this work, I'm using a general combination of identifying the formations based on their distinct lithologies. I assume that Tubbs' interpretation was tied to wells that he had access to inside Aramco, which further confirms the thinking used in our interpretation and my outcrop to seismic tie. Using the picks made by Tubbs', a characterization of the formations based on lithology, and shape, I came up with a lithostratigraphic interpretation of the seismic section that splits the section into the following major packages: the basement and pre-rift – syn-rift (wajh/burqan) – Maqna group – halite (Mansiyah formation) – and post salt

In interpreting seismic reflections, the idea is to use regional horizons to understand the structural setting and be able to carry the interpretation across different lines. I defined three main reflection horizons: Basement, Maqna (base of salt), and top of salt.

Basement reflection

Starting the interpretation from the base of the sedimentary section, the basement is defined as the crystalline rock that's at the base of the sedimentary section. The basement is identified on the seismic image as the lowest strong reflection forming the base of the rift section. The reflection can be tied to the outcrop in several places. I also calibrated my interpretation with Tubbs et al. (2014) interpretation and tied to it visually as close as I could.

Magna reflection

The base of salt reflection is a regional pick that can be easily identified. The base of the salt layer, often marked by the transition from halite to anhydrite, is a prominent regional seismic pick due to its strong acoustic impedance contrast. This reflection is typically one of the strongest in a seismic section, as anhydrites exhibit significantly higher acoustic impedance compared to halite or clastic sediments. Such impedance contrasts make anhydrites distinct and easily identifiable in seismic reflection surveys, as described by Sheriff and Geldart (1995), who emphasize their diagnostic seismic response in stratigraphic and structural interpretations.

Top salt reflection

The top of the salt layer is a key regional seismic pick, often identified by the transition from overlying sediments to halite. This boundary is characterized by a significant decrease in acoustic impedance, as halite typically has a lower impedance compared to clastic or carbonate sediments.

The contrast results in a strong negative reflection, making it a reliable marker in seismic surveys. Sheriff and Geldart (1995) note the top of salt as a critical horizon for subsurface interpretation, particularly in regions dominated by evaporite tectonics. To add to that, the reflection is easily picked from the behavior of the salt due to its mobility where the overlaying structure onlaps the top of salt and it acts as a detachment surface.

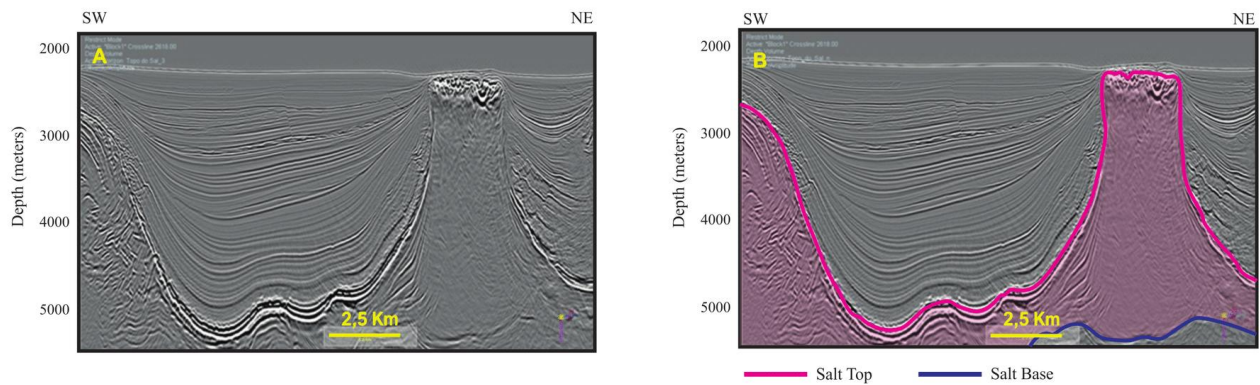


Figure 5 example of a salt diapir in a seismic section (Wagner et al.)

3.2.3 Fault Interpretation

Faults on the seismic section show up as lateral breaks in the horizon and cause discontinuities in the horizon. The faults that exist in the region are either rift faults or strike-slip faults. The rift faults are the basin bounding faults that give the basin the classical wedge shape in the syn-rift section. The sedimentary layers represented by the seismic horizons appear dipping towards the fault plane as the pre-rift layers rotate while slipping along the fault plane. The syn-rift faults deposit along while the fault is creating accommodating space, which is the biggest and closest to the faults, resulting in the sedimentary packages thickening towards the fault plane. The final package of the sedimentary section that relates to the rift fault is the post-rift section, where the faults stop moving, and the deposition fills up the existing space and deposits layers that become flat again.

Strike-slip faults show up as sub-vertical discontinuity that shows up cutting all the formations, and it doesn't affect the thickness of the layers because it post-dates their deposition.

3.2.4 Lithology Characterization

This was coupled with the fact that the Red Sea sedimentary section has distinct lithology groups and kinematic history that can be used to guide the interpretation

Salt Bodies

Salt formations were characterized by their chaotic and low-amplitude seismic facies, which are commonly observed in evaporite sequences. Techniques for salt characterization in seismic data are outlined by Jackson and Hudec (2017). We can see from a seismic section in figure 5 a typical salt body with transparent zone in the seismic where the salt is.

Anhydrites:

Anhydrite layers were identified as very strong, continuous reflections, following guidelines in seismic lithology analysis provided by Chopra and Marfurt (2007). The Anhydrites were picked based on the information detailed in Tubbs et al (2014). The Anhydrites of the Maqna group are picked on the seismic sections in Tubbs' paper as the bright reflector that is at the base of the Mansiyah halite body.

Rollover Anticlines

Salt rollover structures form when layered sediments deform over a mobile salt layer that migrates laterally under differential pressure. This salt migration, often from high-pressure zones towards low-pressure spaces (e.g., faults or structural lows), causes the overlying strata to arch or fold, creating a characteristic anticline structure known as a “rollover.” These structures are common in passive margins or rift basins where the salt layer flows due to tectonic extension or differential loading, and they typically align with faults that allow space for salt migration. As described by Jackson and Hudec (2017), salt rollovers develop as the overburden accommodates the displacement of salt, leading to both extensional faulting and the development of structural traps, which are important for hydrocarbon exploration in areas like the Gulf of Mexico and the Red Sea

Basement

I picked the basement here as the lowest strong reflection. It’s tied to the outcrop where possible, and it’s consistent with Tubbs et al (2014) published interpretation

3.2.5 Tie to existing and published data

Tie to published seismic interpretation

Tubb’s paper contains the only published interpreted seismic that was tied to wells from Aramco operations in the Midyan area. This holds valuable information that I used to ground truth my interpretation of the new seismic and build the regional story. The seismic was published with a rough map location. However, I used their index map to tie the shoreline and project the line

locations on the map. I also scaled the depth to tie the seismic together. The tie was poor, but it gave a very good indication of where each horizon pick roughly was. In guiding the structural interpretation of the section, however, I feel it's adequate.

Correlation of Seismic and outcrop Data

Surface faults identified in the satellite mapping were correlated with subsurface faults interpreted in the seismic data to develop a unified fault model. This integrated fault model allowed for cross-referencing of fault characteristics between seismic and surface observations, following cross-correlation methodologies by McClay and Dooley (1995), which emphasize combining field and seismic interpretations for accurate subsurface models.

Basin Restoration Based on Published Spread Rates

Restoration of the basin along the strike-slip direction using established spreading rates for the Red Sea region to model the configuration prior to the initiation of the Gulf of Aqaba system. This restoration method, relying on techniques developed by Tapponnier et al. (1982), utilizes plate tectonic reconstructions to back-track basin evolution based on kinematic rates. I'm using the restored outlines created by delaunay et al (2023)

Extension of Gulf of Suez Structural Framework to Midyan

The Gulf of Suez fault framework was extended southward to include the Midyan area by analyzing structural continuity in normal and transform fault systems. This extension follows the methodologies Bosworth (1993) outlined, who characterizes structural transitions along the Red Sea and Gulf of Suez, facilitating tectonic interpretation across basin boundaries.



Figure 6 image of a strike-slip zone showing the propagation of the displacement and the space creation typical of this type of fault system

CHAPTER 3

RESULTS AND CONCLUSION

4.1 Results

4.1.1 Fault on Satellite Imagery

Since strike-slip faults typically exhibit horizontal motion along relatively straight fault traces, their mechanics and motion are well-illustrated in map view. In an ideal case, a flat, planar strike-slip fault does not produce notable vertical displacement, meaning minimal associated topography exists. However, extensive strike-slip faults often exhibit a stepped, stair-like pattern composed of straight fault segments (akin to vertical "flats") connected by oblique bends or jogs (analogous to vertical "ramps"). This undulating fault geometry is also visible in 3D seismic images and remote sensing data, reflecting the connection of alternating fault segments that evolve over time.

Normal faults are visible in satellite imagery and remote-sensed data as linear or arcuate features that reveal characteristic down-dropped blocks (grabens) or raised blocks (horst). Morphological clues, such as fault scarps that produce linear topographic breaks or tilted layers, are particularly helpful in mapping normal faults from above. We can also confirm these faults in field mapping and then trace them on satellite imagery. My first step was to identify fault trends on satellite images; then, I visited the sites to confirm the major faults in the field and delineate them on satellite images.

The expected fault type depends on the zone the fault was picked, the formations it juxtaposes, and the trend. I categorize the trends into the Red Sea and Aqaba trends. The Red Sea trend is generally parallel to the Red Sea and is expected to be a normal rift fault.

The Aqaba trend is a strike-slip system. The main fault segments would be parallel to the Gulf of Aqaba, but strike-slip faults bend and interconnect in releasing or constraining bends that can cause it to have sections that are perpendicular in trend to the Gulf of Aqaba. We can easily tell from the displacement trend if it's a strike-slip, and in the flats of the Midyan area where Ghawwas is the basin floor, it's very easy to pick on satellite images, as I will show next. All the displacements along these strike-slip faults are left lateral and have different displacements and propagation lengths. Picking these faults can be easy when juxtaposing different lithologies like the anhydrites and clastics. However, a feature that has become apparent in satellite imagery is the circular patterns of salt rollover anticlines and turtle structures. These features are present in the satellite image as circular features and are confirmed by seismic profiles, as shown in the following sections. When the strike-slip fault propagates through it, it becomes easy to pick as it offsets the rings of the anticline, clearly marking its displacement from a bird's eye in a way that's more difficult to pick while standing in the field.

Picking the Red Sea trend in the satellite image

Red sea faults are basin-bounding and can easily be picked parallel to the shoulder. These faults are uplifted and rotated where the Wadi Waqab overlies the basement with both formations

exposed. These faults are easy to pick and delineate along the Red Sea. When we get to the Midyan basin, we pick it along the edge of the mountains where the basement is lifted kilometers in the air and Ghawwas in the flats overlaps it.

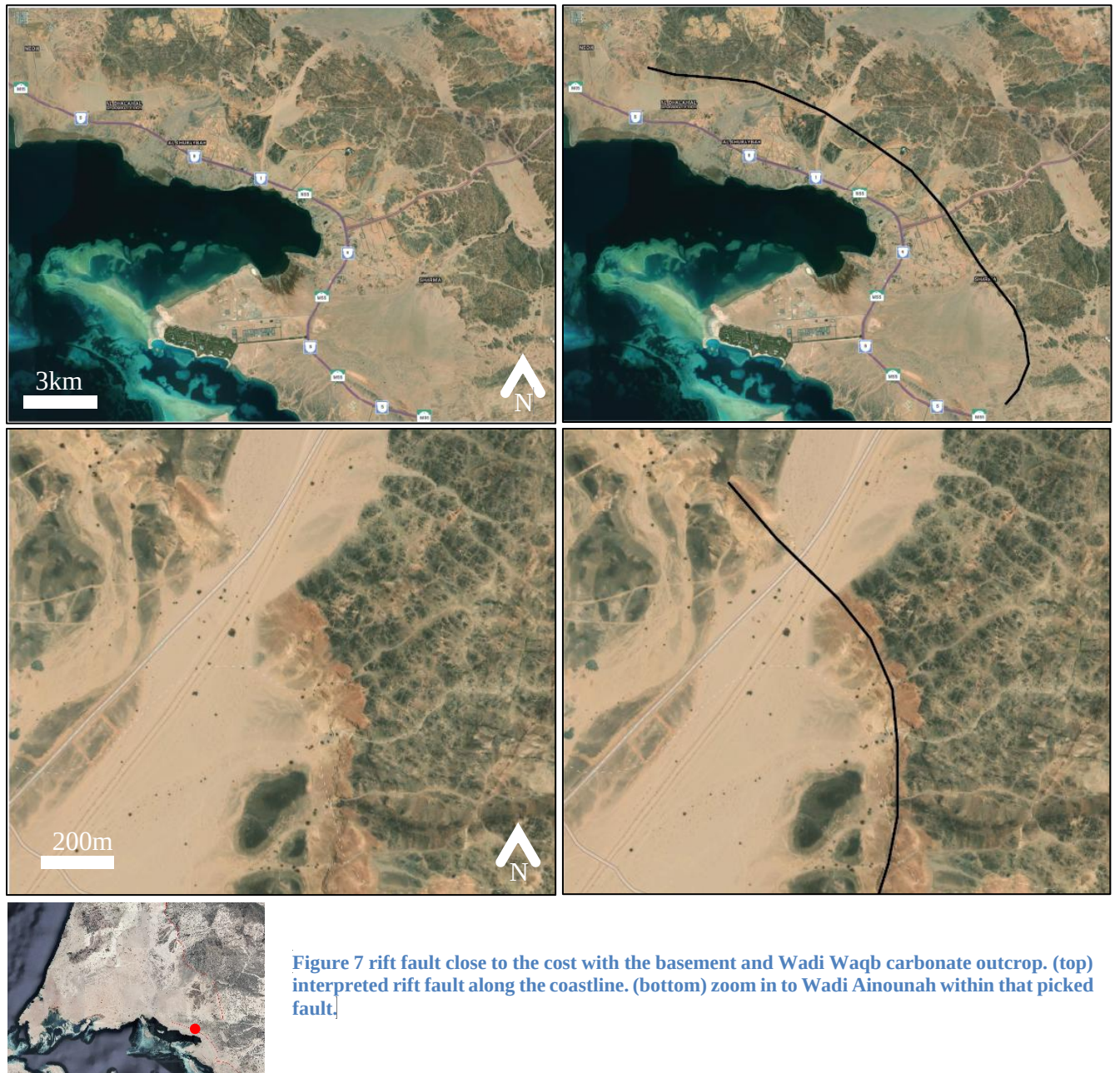


Figure 7 rift fault close to the coast with the basement and Wadi Waqb carbonate outcrop. (top) interpreted rift fault along the coastline. (bottom) zoom in to Wadi Ainounah within that picked fault.



Figure 8 Satellite image with picked rift faults in red

Picking anticlines in Ghawwas

Anticlines in map view can be identified by their characteristic folded geometry, where older rock layers are exposed in the core, flanked by progressively younger layers. In the Midyan region, picking anticlines is critical for interpreting salt evacuation processes and understanding the area's post-Red Sea rift kinematics. Following the cessation of the rifting, salt deposits accumulated in the basin, capped by the Ghawwas clastic deposits. Subsequent mobilization of the salt led to the formation of rollover anticlines and turtle structures, which provide evidence of salt tectonics. These structures were later offset laterally by strike-slip faulting, preserving a clear chronological record of deposition, salt mobilization, and fault activity. Furthermore, when strike-slip faults are observed surrounding the evacuation features, it may indicate that salt evacuation was initiated or

influenced by strike-slip tectonics. This suggests that the salt mobilized in different sequences, reflecting variations in the timing and mechanisms of deformation. Mapping these relationships allows us to reconstruct the structural evolution of the basin, offering insights into the interplay between salt tectonics and strike-slip faulting.

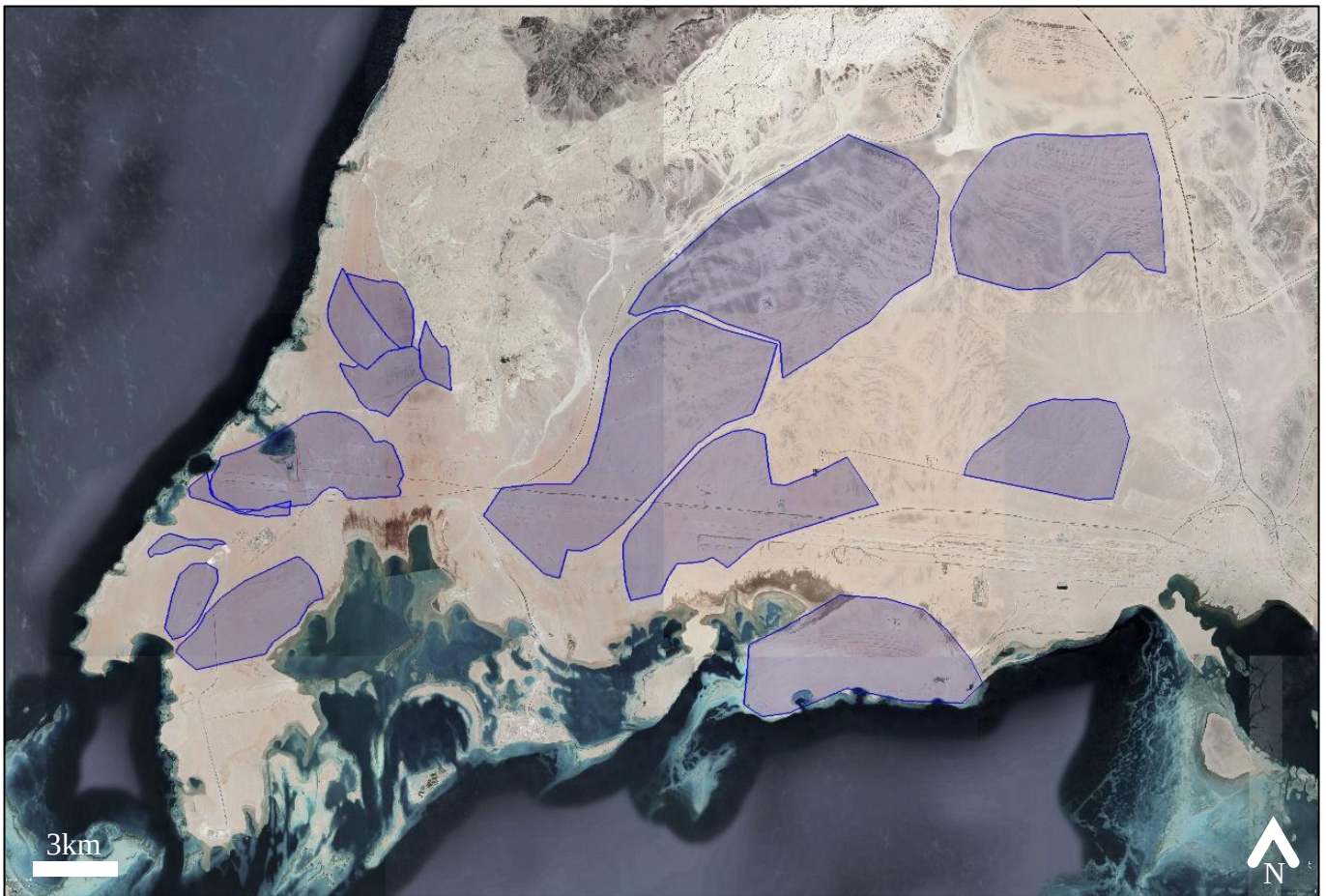


Figure 9 polygons highlighting the different evacuation structures in Ghawwas

Picking Gulf of Aqaba trend in the satellite image

The horizontal left-lateral motion, estimated at ~ 5 mm/year, dominates the tectonic activity, with additional evidence of vertical deformation resulting from irregular fault geometry and interactions with the Red Sea's spreading dynamics. On the Saudi side, the fault extends onshore, influencing

local geomorphology and providing insights into the tectonic history through features like uplifted marine terraces, which have been extensively mapped and dated to reconstruct the fault system's evolution. We can see onshore the vertical displacement mapped and is imaged in seismic. We pick onshore from the satellite image 2 different methods of picking these strikeslips: one when displacing and uplifting Magna formation against Ghawwas, and one when displacing the ghawwas anticlines causing the rings on the surface to offset against each other (figure 10)

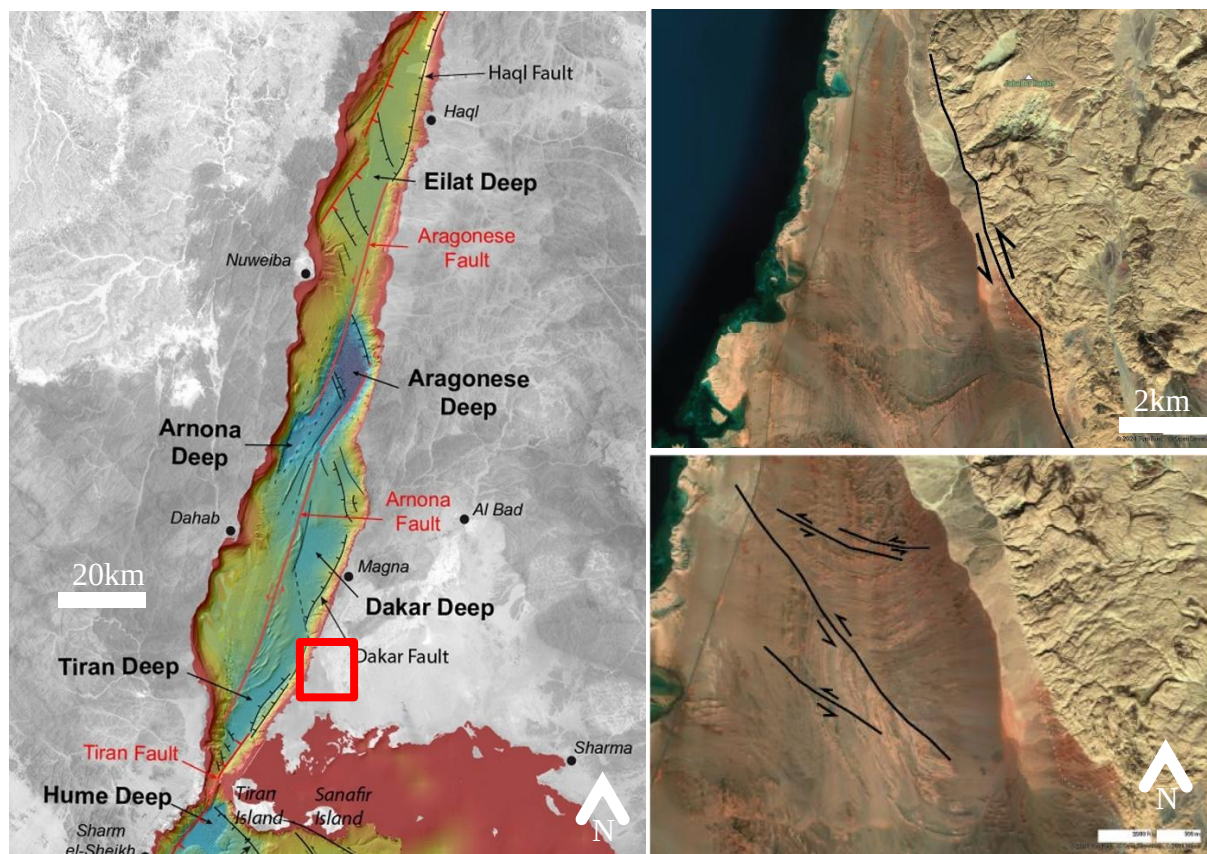


Figure 10 (left) modified from Ribot et al. I (2024) showing the overall structure in the Gulf of Aqaba and in a square red one of the locations we delineated offshore faults in the onshore. (right, above) the delineated offshore fault picked on satellite image j

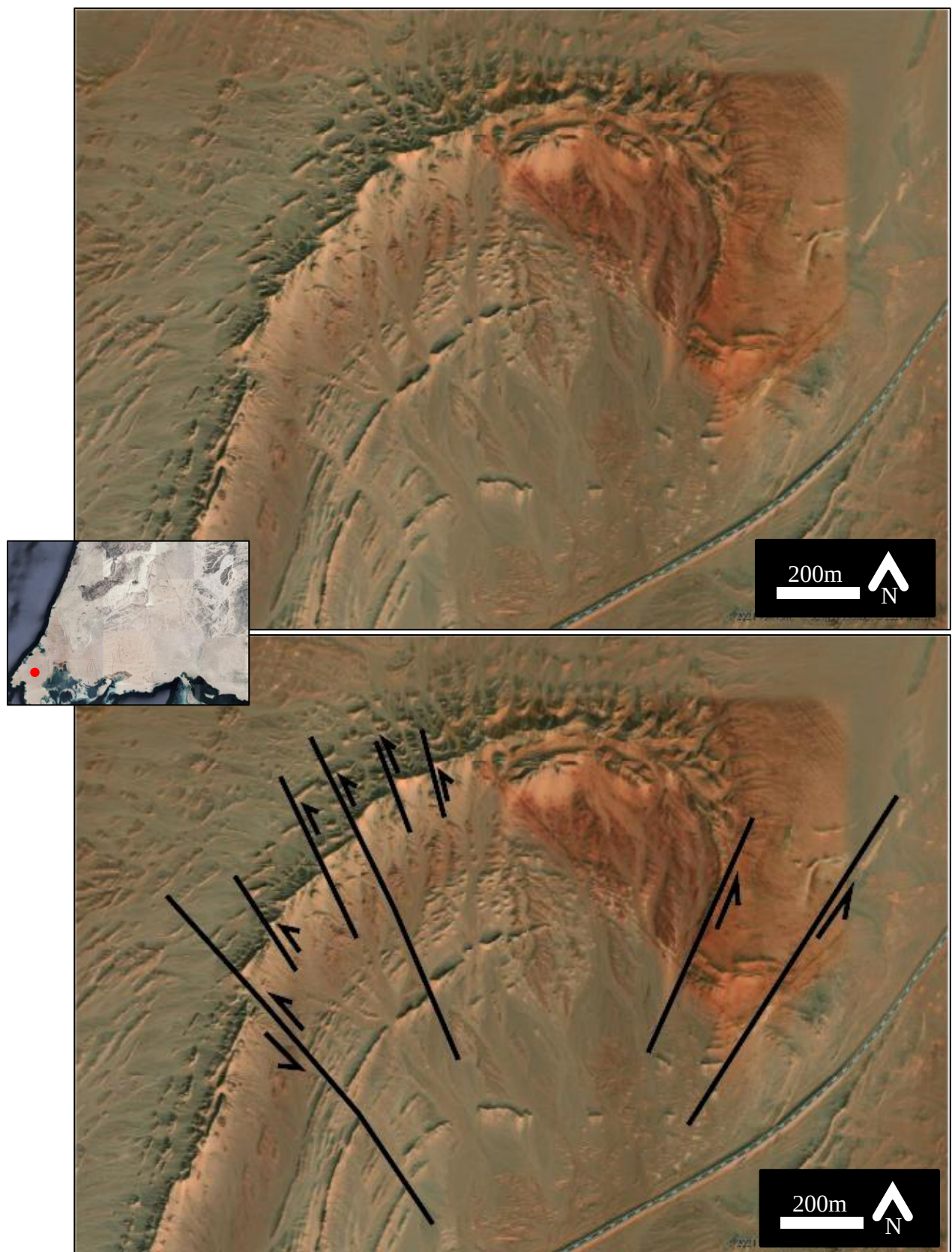


Figure 11 satellite image of a Ghawwas anticline that got broken up by propagating strike slip deformation that displaces the rings formed by the anticline internal layering. (middle, left) regional satellite image showing the location indicated by a red dot of it



Figure 12 satellite image with rift faults in red, and strike-slip faults in brown

4.1.2 Tie to Outcrop

Outcrop mapping plays a critical role in understanding regional geology by providing direct, observable evidence of lithology, structural features, and stratigraphic relationships. By examining exposed rock units, we can identify fault systems, folds, and other tectonic structures essential for reconstructing geological histories and regional tectonic settings. Outcrop data also provide ground-truth validation for interpretations made using remote sensing and geophysical methods, ensuring that subsurface models accurately reflect surface observations. This approach is particularly valuable in regions where geological features, such as faults or sedimentary layers, are well-exposed, offering insights into processes like deformation, sedimentation, and magmatism. Key methodologies are discussed in Twiss and Moores (2007), emphasizing the integration of outcrop observations with broader regional analyses.

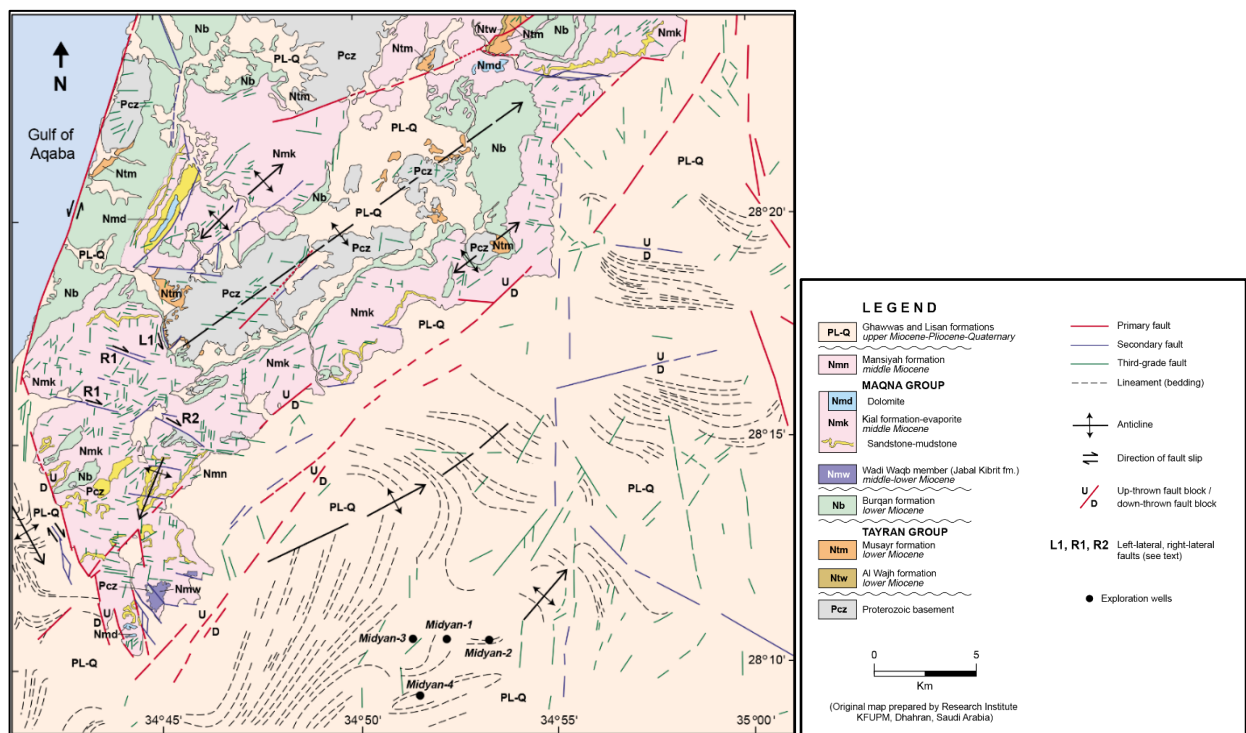


Figure 13 Geologic map of the western part of the Midyan region. Hughes, et al. (1999)

Rift fault outcrop (wadi Ainounah)

Wadi Ainounah is a famous valley in NEOM that has been extensively studied by different science sectors as it's considered a classic rift fault outcrop. it holds a well-preserved archeological site and is a local favorite picnic location in general.

The location to our interest is an exposed fault tip where the top basement is juxtaposed against carbonate rocks. The top of the basement section is covered in carbonates as well. This shows a classic rift geometry for syn-rift lithology where the carbonates fill up accommodation as it becomes available. These carbonates are proposed to be the Wadi Waqab formation of the maqna group (Tubbs et al., 2014), but I couldn't find an age dating data to confirm it. These carbonates are in general assumed to be the maqna groups and they cover the basement all over the red sea and are generally accepted to be that way based on the existing geologic maps. This outcrop serves to show an analog for the seismic interpretation I did as it reflects the geometry of these formations and faults very clearly and is the typical rift fault geometry.



Figure 14 Wadi Ainounah outcrop. (Top) The outcrop image shows Wadi Waqb in green and the rift fault. (Bottom, left) satellite image with Wadi Ainounah location. (Bottom, right) zoomed in on the satellite image with picked rift fault.]

Strike slip fault (Gulf of Aqaba fault)

This fault is a big strike-slip trend that's clear on the satellite image and juxtaposes the Maqna anhydrites against the ghawwas. This fault is also imaged on the seismic lines and is a major strike-slip fault that represents the edge of a pop-up structure. When I visited the outcrop location, we could see subvertical beds, as well as ductile flow in shales. This represents a major fault in the area (figure 15). In the following figures (figures 16-17), we see other outcrops showing clear strike-slip deformation that demonstrates the wide spread zone for this strike-slip trend.

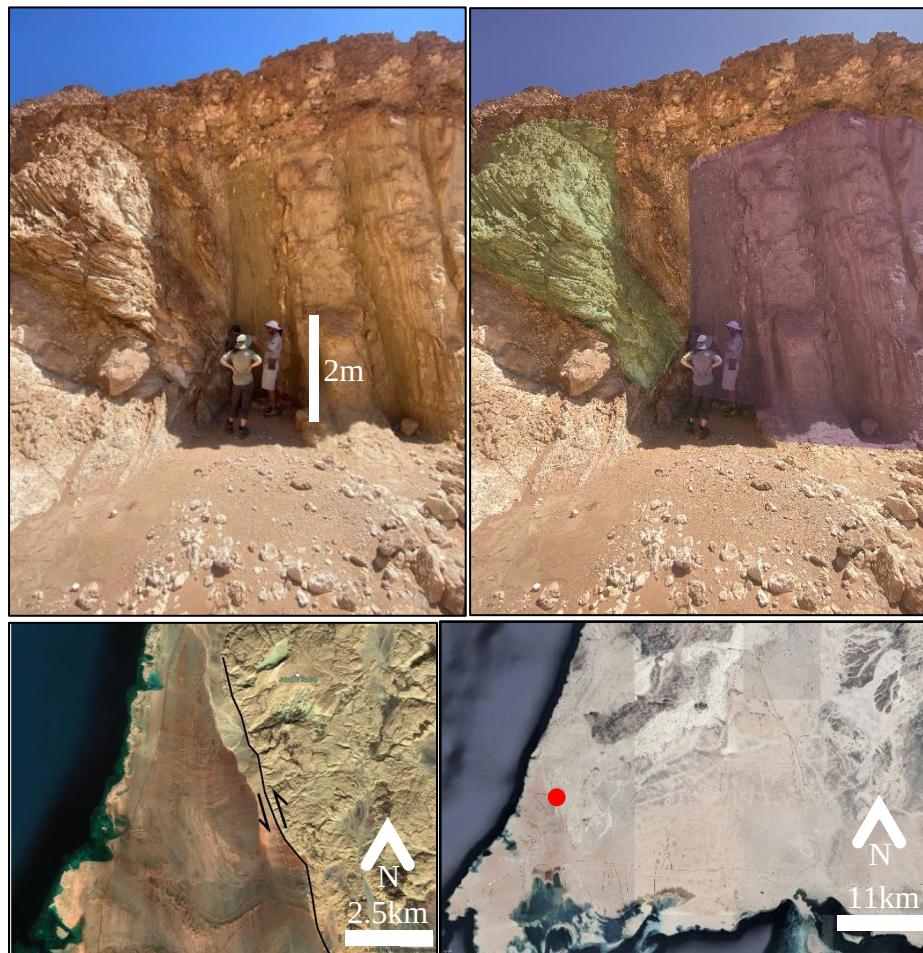


Figure 15 outcrop and satellite view of the major strike-slip fault juxtaposing Maqna group and Ghawwas formation north of Ras Shiekh Humaid. (TOP) image of the outcrop showing sub-vertical beds and an enormous fault gauge. (Bottom) satellite image showing the lo



Figure 16 Maqna group sandstone faulted by strike-slip faults within the same trend of displacement

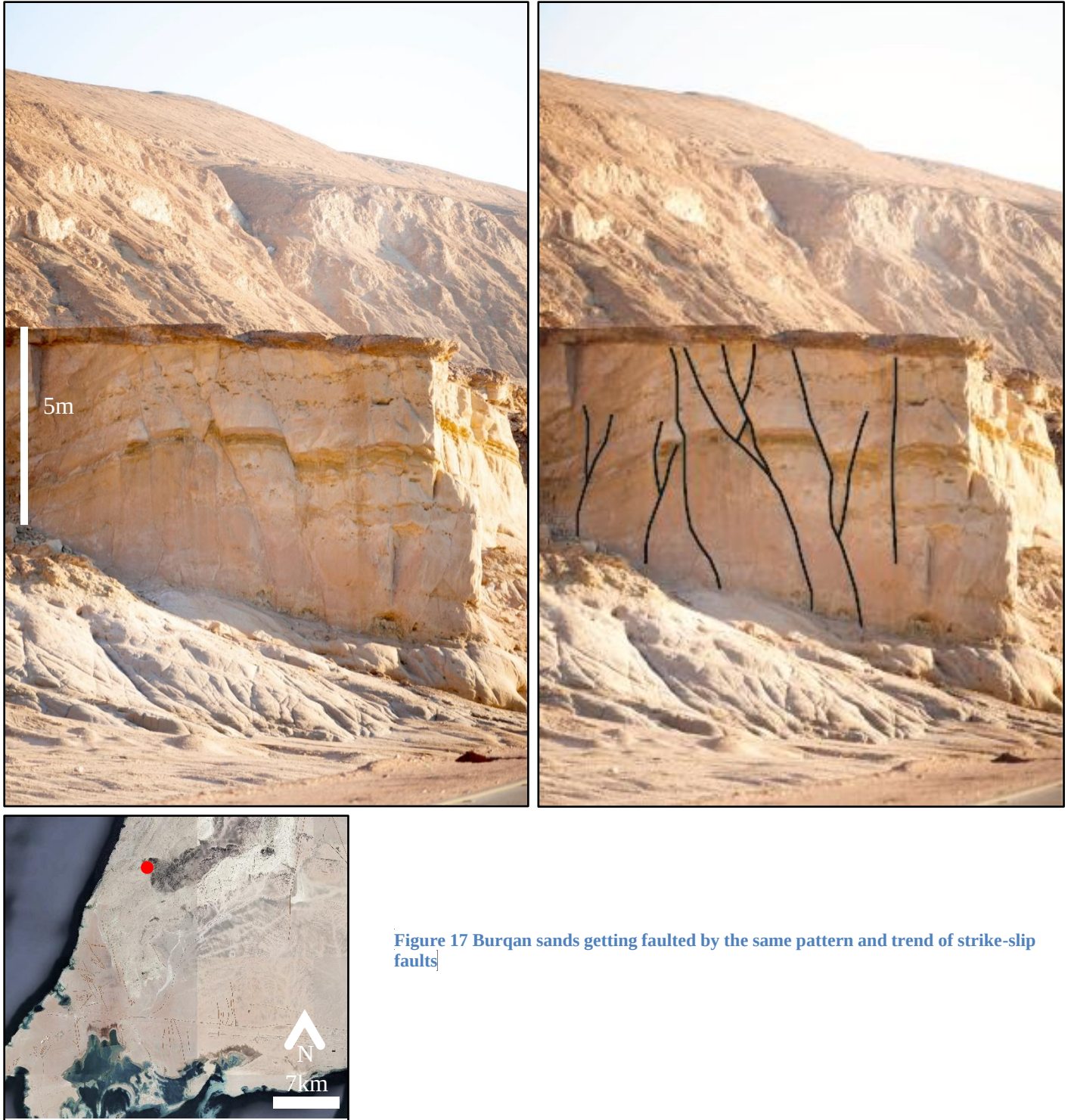


Figure 17 Burqan sands getting faulted by the same pattern and trend of strike-slip faults

4.1.3 Seismic Profiles: Available Seismic Lines

I'm using a combination of published seismic lines that I've approximated the locations to based on the location specified in the paper and newly acquired seismic lines shot by NEOM that they have made available and allowed me to use. The lines starting with N are the new NEOM lines.

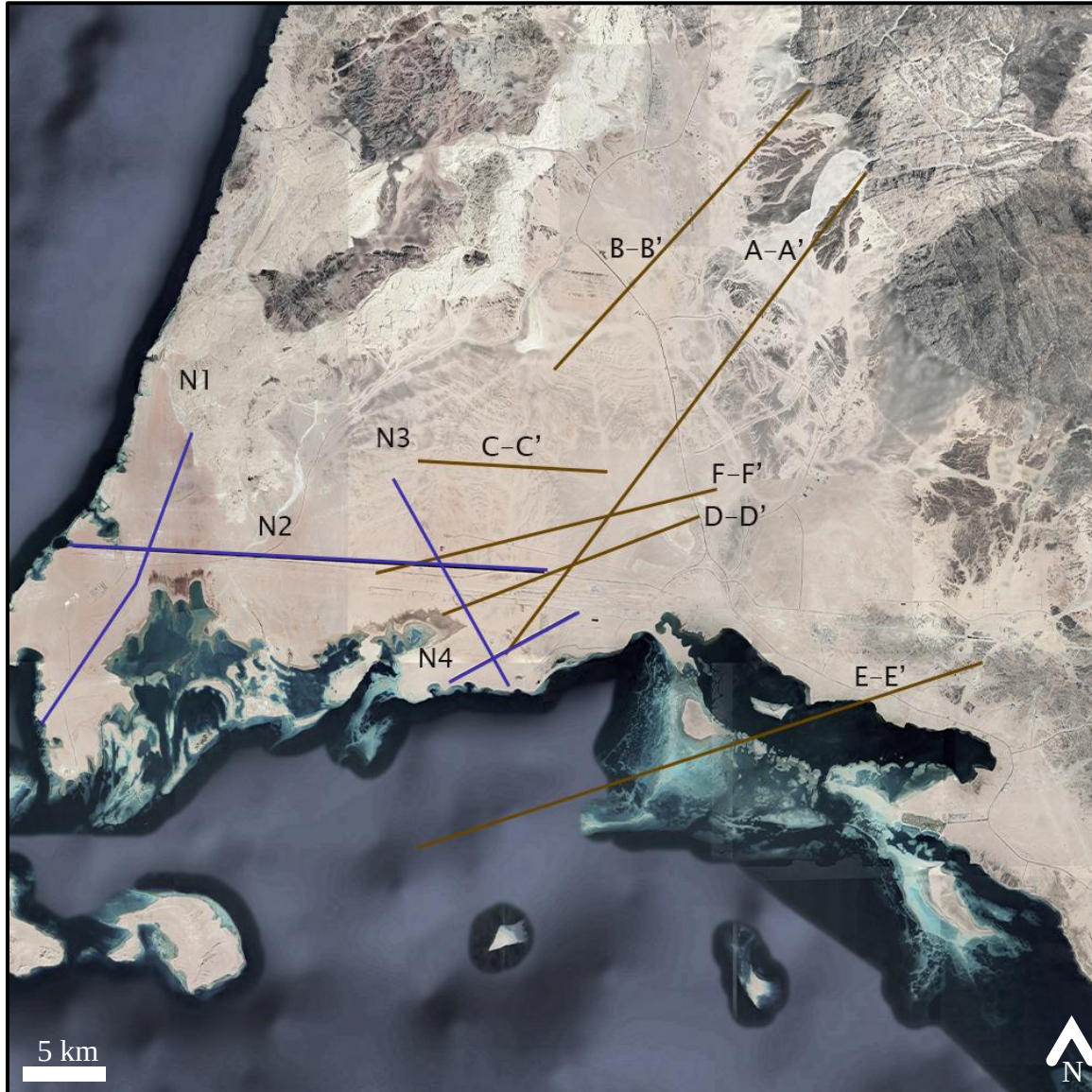


Figure 18 Satellite image with the seismic lines both published and newly acquired by NEOM. The brown colored lines are the ones published by Tubbs et al. (2014), and the blue lines are newly acquired by NEOM.

Published Seismic Profiles

The following seismic lines (Tubbs et al. 2014) are from 3D pre-stack depth migrated data that's tied to Aramco wells. Although the exact location wasn't known, I approximated the location by superimposing the index map on a satellite image to get the line locations of these published profiles. This is an adequate approximation to understand the regional basin architecture and calibrate the interpretation of the new lines based on basin geometry, relative reflection character, and the general behavior of the reflections.

Line A-A'

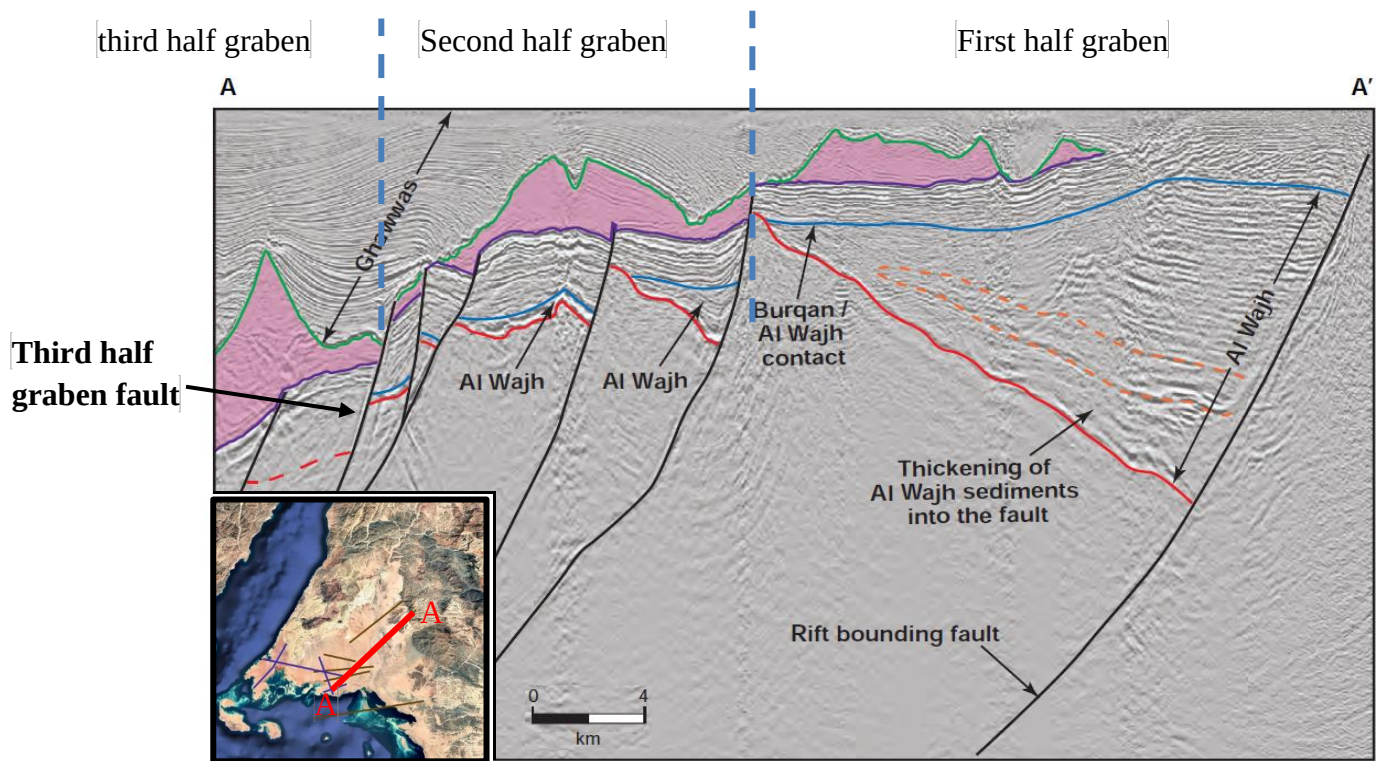


Figure 19 modified A-A' seismic line from Tubbs et. al (2014)

This line provides a tie to the uplifted shoulder in the Midyan basin and images the basin bounding fault and back 1st onshore graben. It also provides a dip azimuth to the structure, showing the first, second, and third rift half grabens. The first half-graben is the oldest and is filled mainly with Wajh formation, as interpreted by Tubbs et al., and the second is the younger one, filled with Wajh and Burqan/Maqna, as interpreted by Tubbs et al. The third half-graben is where this line ties to the newly acquired NEOM lines that I will show next. The third half graben here shows to have been re-mobilized within the Ghawwas time as it is offsetting the base of Ghawwas with growth against it, while the layers beneath the salt aren't showing any growth (figure 20). We can clearly see that the Ghawwas is thickening with the salt evacuation to against that fault and the maqna had experienced no growth against it.

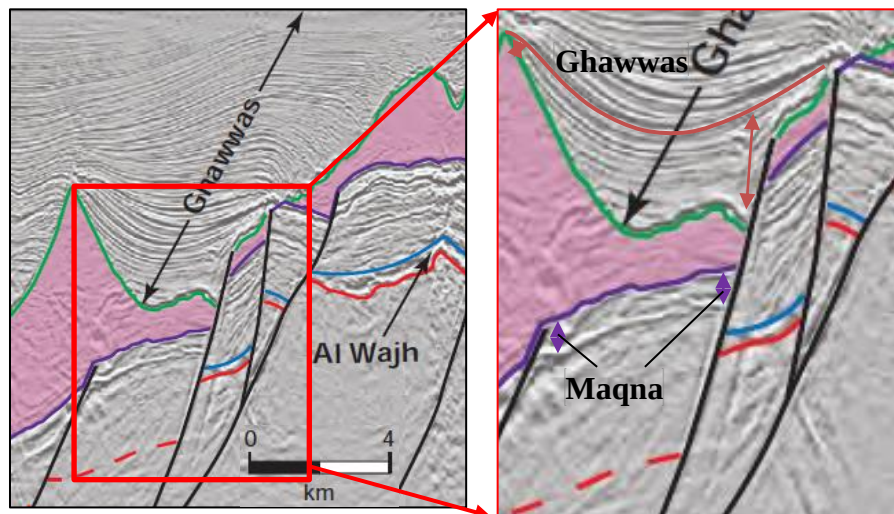


Figure 20 zoom in to the third half graben where Ghawwas is growing a fault that appears to have seized during Maqna indicating a reactivation of the rift fault around the strike slip initiation time

Line B-B'

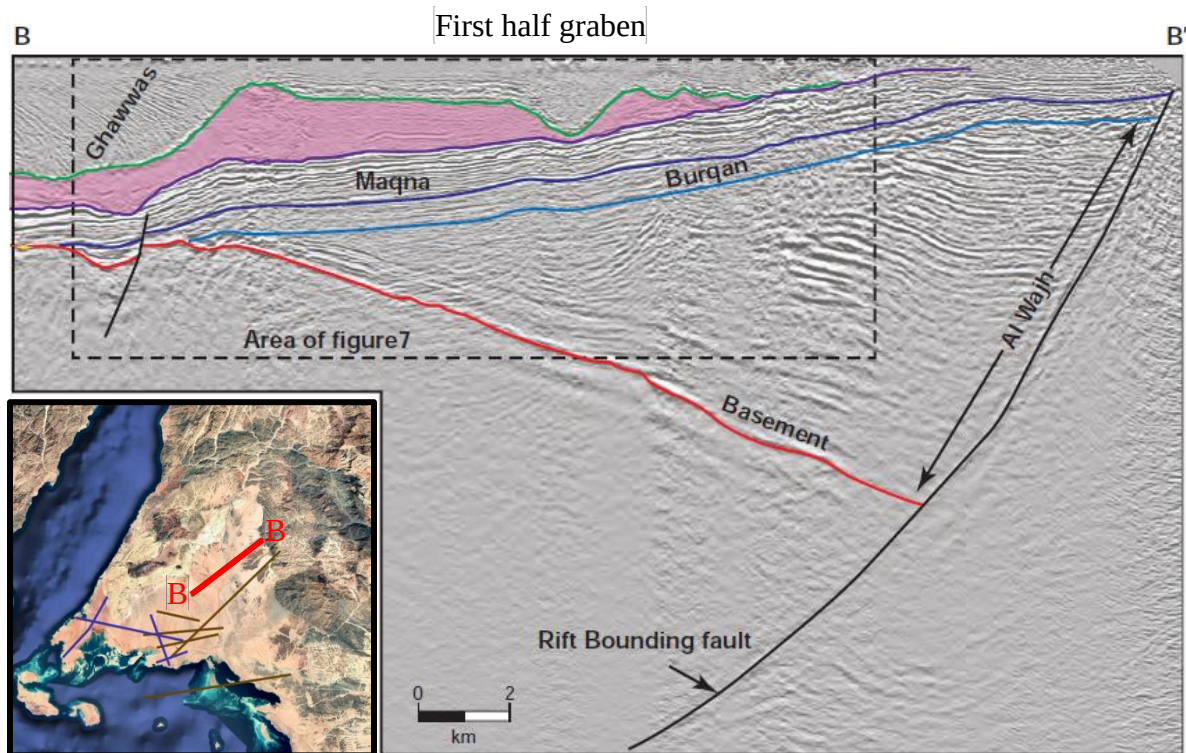


Figure 21 Seismic line B-B from Tubbs et al. (2014)

In this line, based on the interpretation of Tubbs et. al, and the location of the line we see the first half graben imaged, and the rift bounding fault that forms the north-south mountain range bounding the eastern flank of the Midyan basin. It also goes further to show that this half graben is mostly filled with Al Wajh formation which means this half graben formed in the earliest phase of the rift during the deposition of the Wajh formation, and mostly became a bypass zone in the basin during the deposition of the later formations. I should also point out that towards the southern tip of the line, we can see Ghawwas formation at the top of the section starting to form a rollover anticline that ties to the anticlines picked a few sections ago in the surface satellite image interpretation I did.

Figure 22 I picked the Ghawwas horizons dipping towards the top of salt as the salt evacuate from underneath it. This structure forms due to salt evacuation and “welds” in place as the salt runs out leaving an anticlinal structure in the overburden with no salt beneath. This anticline gets eroded at the top which leaves a surface expression at the surface of concentric rings that are getting older in age of deposition as you move towards the center.

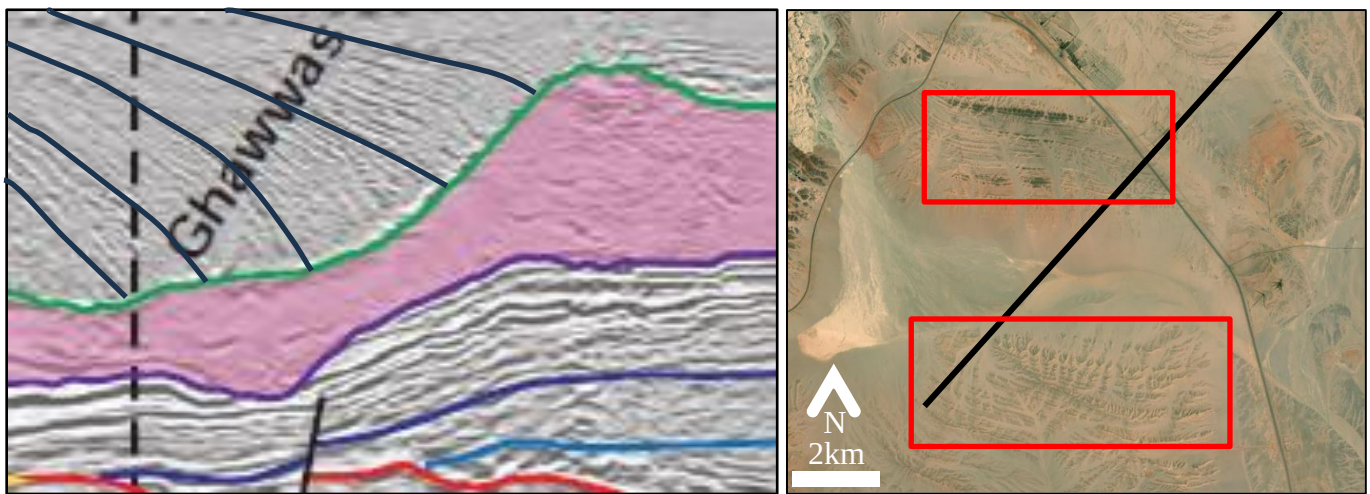


Figure 22 (left) zoom into the top section at the southern end of line B-B' showing the Ghawwas reflectors onlapping the top of Halite. Different reflectors are traced in black to show the pattern. (right) 2 locations where a surface expression of the dipping Gha

Line C-C'

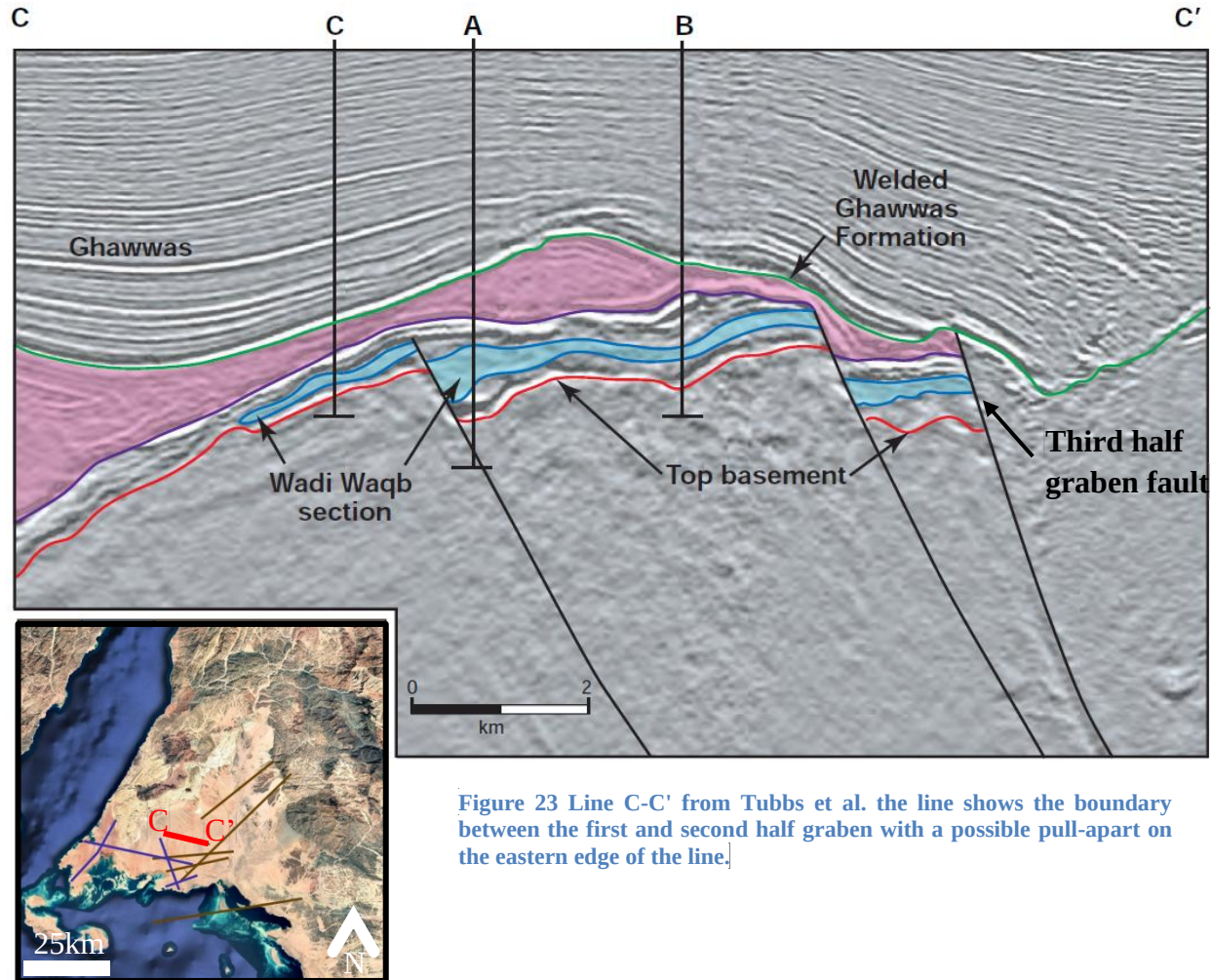


Figure 23 Line C-C' from Tubbs et al. the line shows the boundary between the first and second half graben with a possible pull-apart on the eastern edge of the line.]

In this seismic line, we can see that the Wadi Waqb carbonate is overlapping the basement (similar to the geometry in Wadi Ainounah), which I used to conclude that this is the crest of the third half graben fault in the same structural position as the Wadi Ainounah outcrop. This justifies the lack of earlier deposits, and the reason why of the maqna lithologies, the Wadi Waqb reefal carbonates deposit there. This location is where the Midyan gas field is, and as such, it's very well-constrained and understood. The fault at the eastern edge is either a pure pull apart or got re-activated by the strike-slip deformation. This fault is imaged from a different angle in line A-A' I showed earlier, marking the transition to the third half graben.

Line D-D'

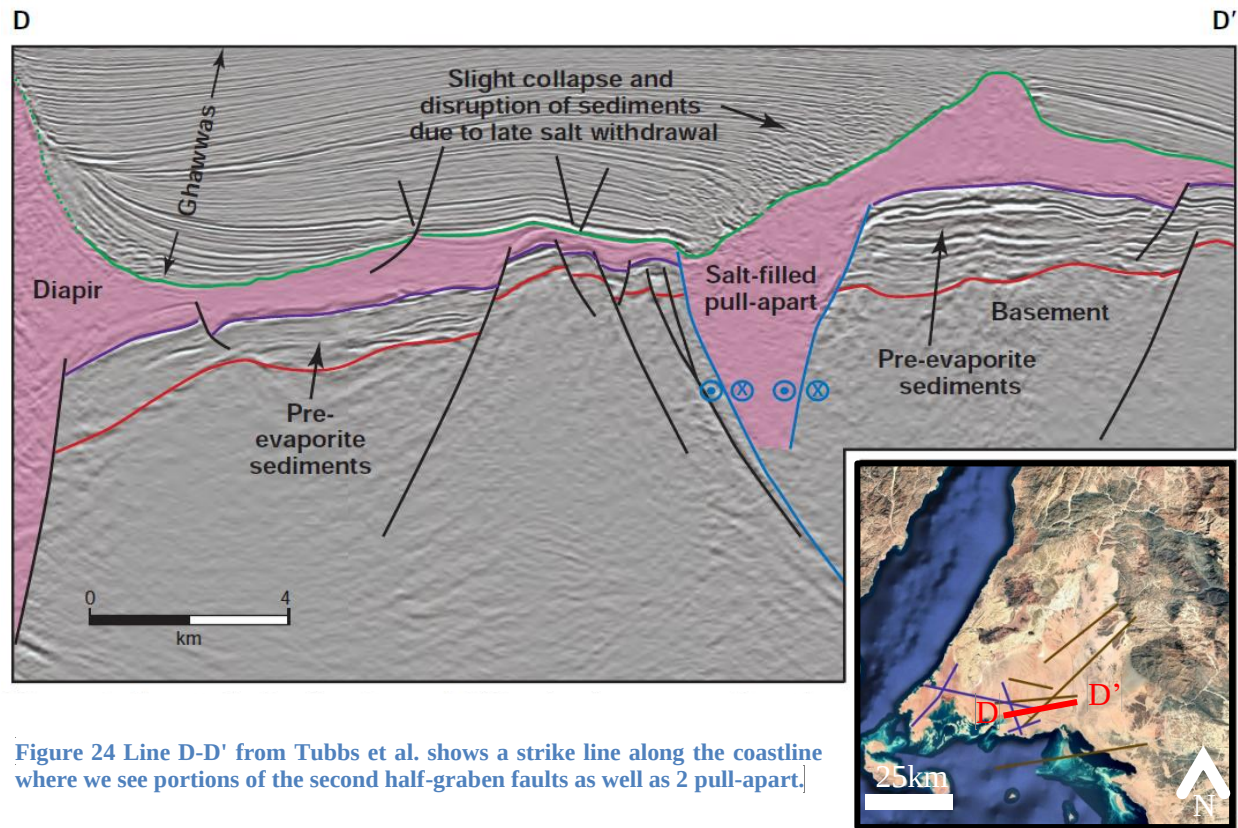


Figure 24 Line D-D' from Tubbs et al. shows a strike line along the coastline where we see portions of the second half-graben faults as well as 2 pull-apart.

In this seismic line, we see a strike direction that moves between the second and third half graben crossing the same pull apart imaged in the previous lines and ending in another pull apart to the west. The line is mostly running in the second half graben, which is apparent In the relatively low thickness of the pre-salt section. The line runs perpendicular to the direction of displacement of the strike-slip, and therefore, the pull-aparts are well-imaged. Strike-slip displacement is what causes the difference in the pre-salt thickness between the area before and after the pull-apart along the line. This is caused by juxtaposing an area closer to the crest of the half-graben down to an area with thicker syn-depositional formation.

Line F-F'

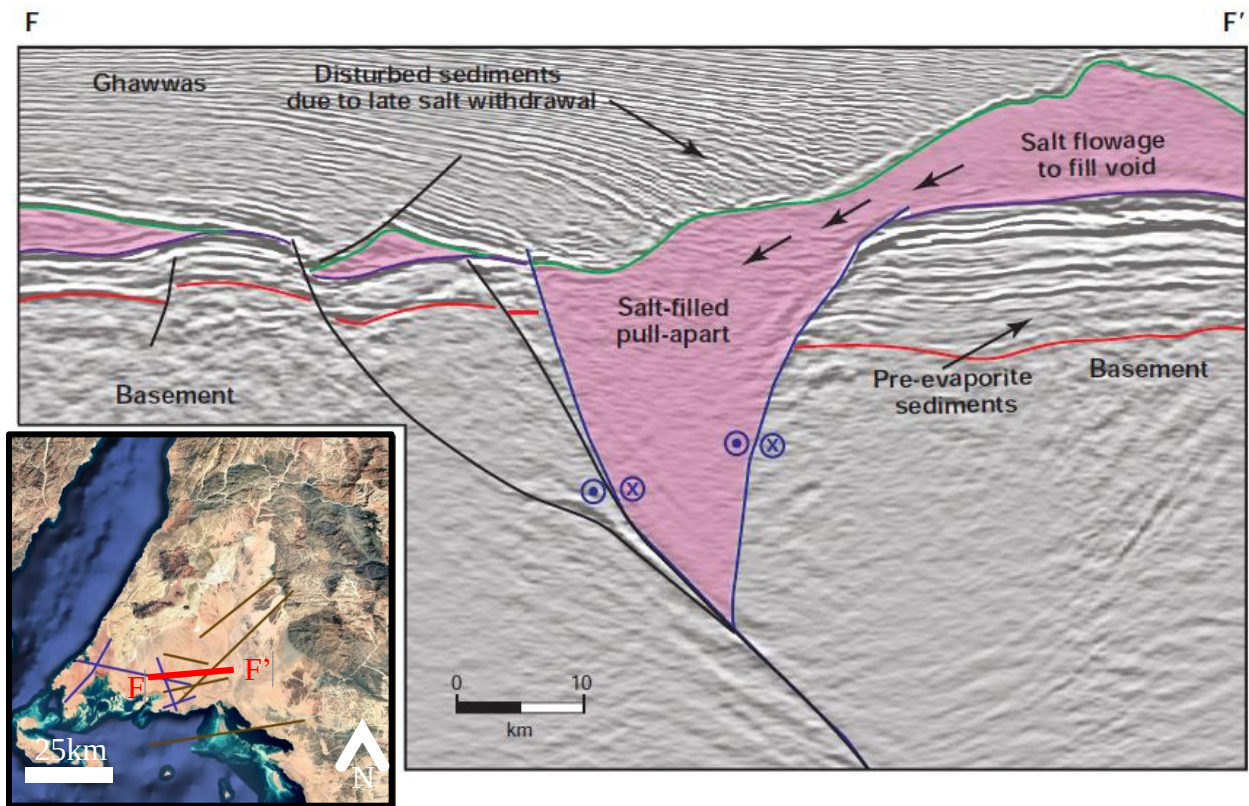


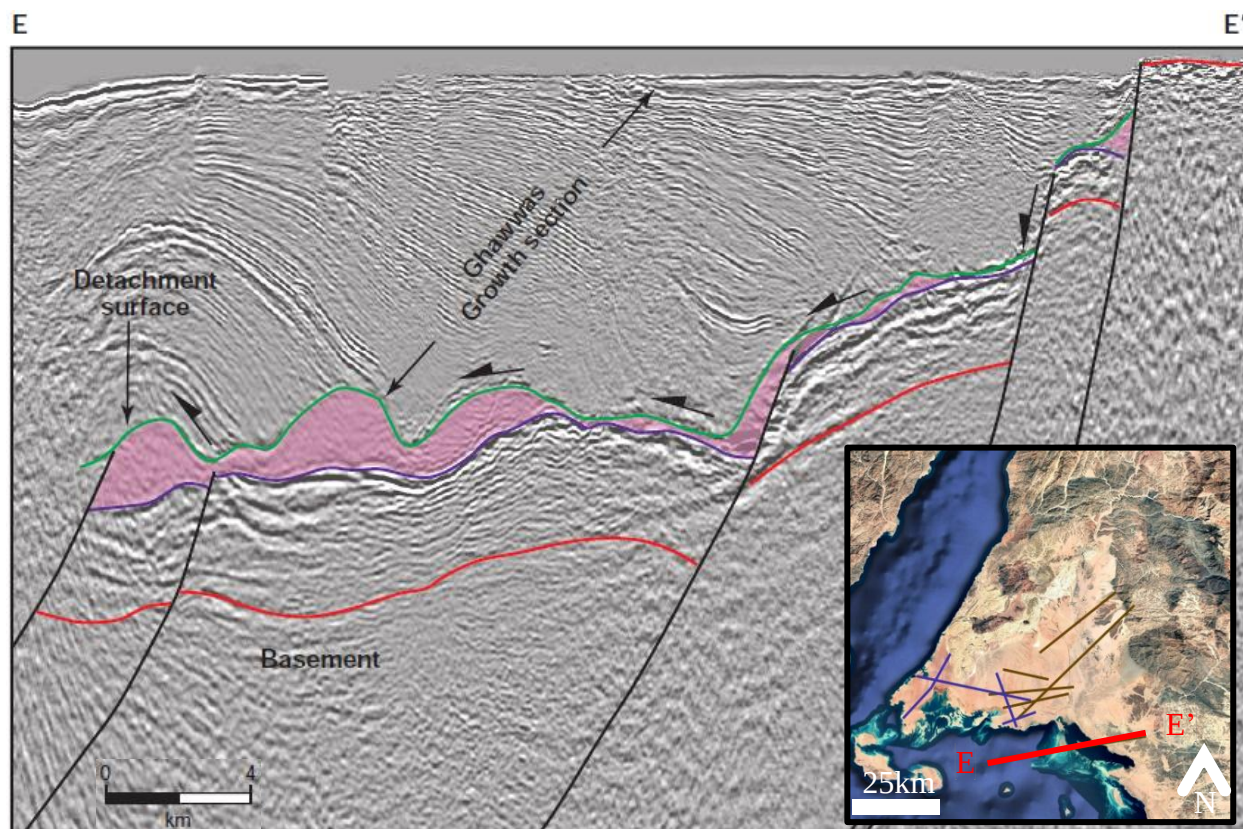
Figure 25 Line F-F' from Tubbs et al. Showing the same pull apart from the previous line.

This line highlights the pull-apart again, showing deformation into the Ghawwas. We can track strike-slip from satellite images along the same trend. This line images the same pull-apart I noted in the previous lines and further demonstrates the juxtaposition from different zones of the second half graben to show a clear change in the pre-salt section thickness across the strike-slip.

Salt structures, such as diapirs, ascend through overlying strata primarily due to their buoyancy, as salt is generally less dense than surrounding sedimentary rocks. This buoyant rise is a key mechanism in salt tectonics, leading to the formation of various geological features. Hudec and Jackson (2007) provide a comprehensive overview of this process, emphasizing that the upward

movement of salt is driven by its lower density relative to the overburden, facilitating the formation of diapirs and other related structures. Based on the above, I would like to note that I disagree with the interpretation presented by Tubbs et al. on the direction of salt flow and its justification. Salt flow is usually directed upwards in the direction of least pressure as directed by the buoyancy effects that cause salt to diapir or flow. The geometry of the overburden points toward an upward flow of the salt as the Ghawwas layers are dropping below regional and onlapping the salt. The rise of the salt is also supported by the evidence of the faults propagating all the way to the surface and displacing the overburden. This suggests that the displacement post dates Ghawwas, and makes it more difficult to justify the salt flowing deeper below the overburden.

Line E-E'



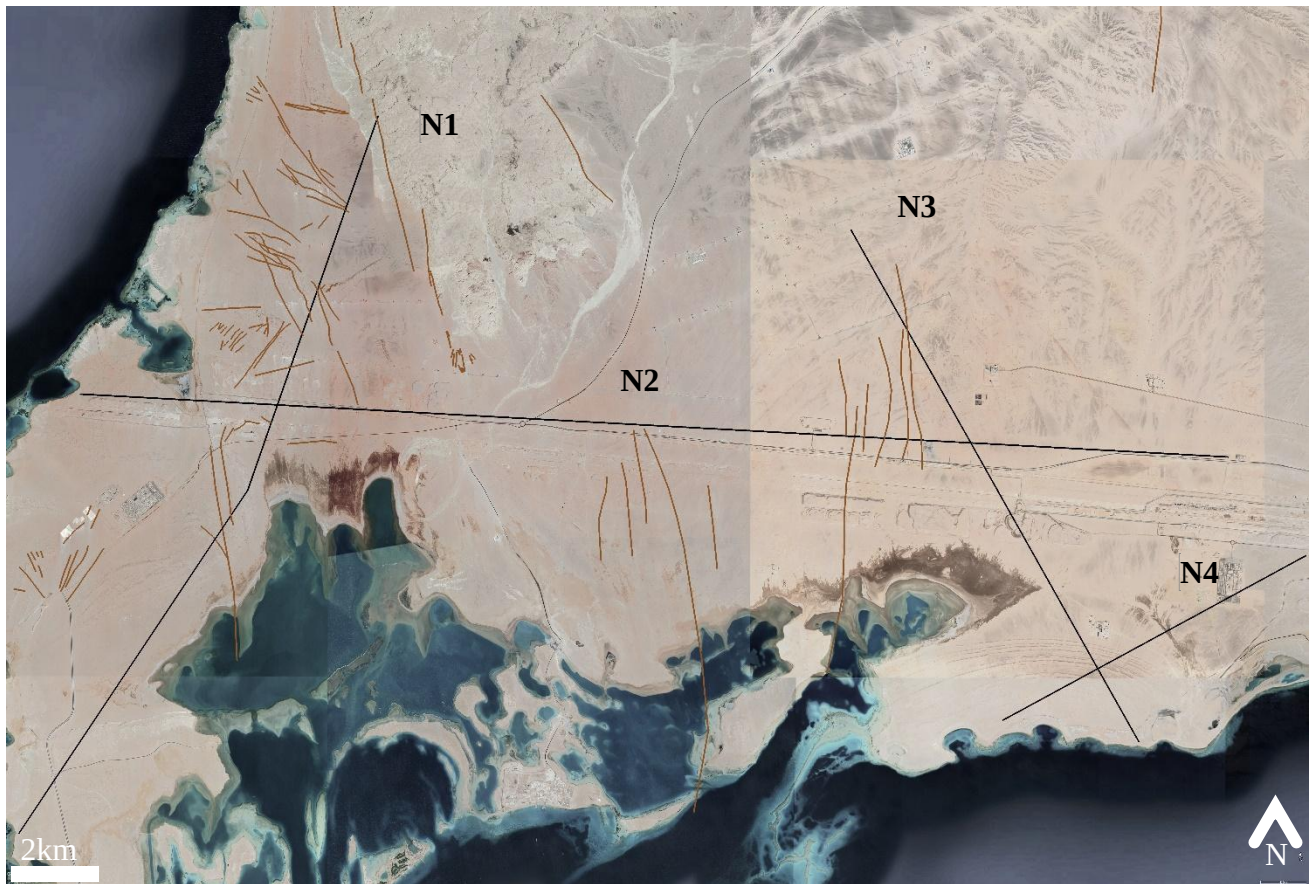
[Figure 26 E-E' seismic line from Tubbs et. al (2014) showing an onshore-offshore line with basement step down]

In this line, we see a regional structure showing the second half-graben towards in full in this area. The eastern uplifted side of the line ties to the basement outcrop in Wadi Ainounah at the outcrop location I detailed earlier, and the western end shows the second half graben fault. This also appears to be a strike orientation or an accommodation space within the rift faults as we don't see any significant change in the pre-salt section thickness. There's no apparent occurrence of strike-slip deformation, and I don't think the effect of the Aqaba fault system extends to this area.

Neom newly acquired seismic

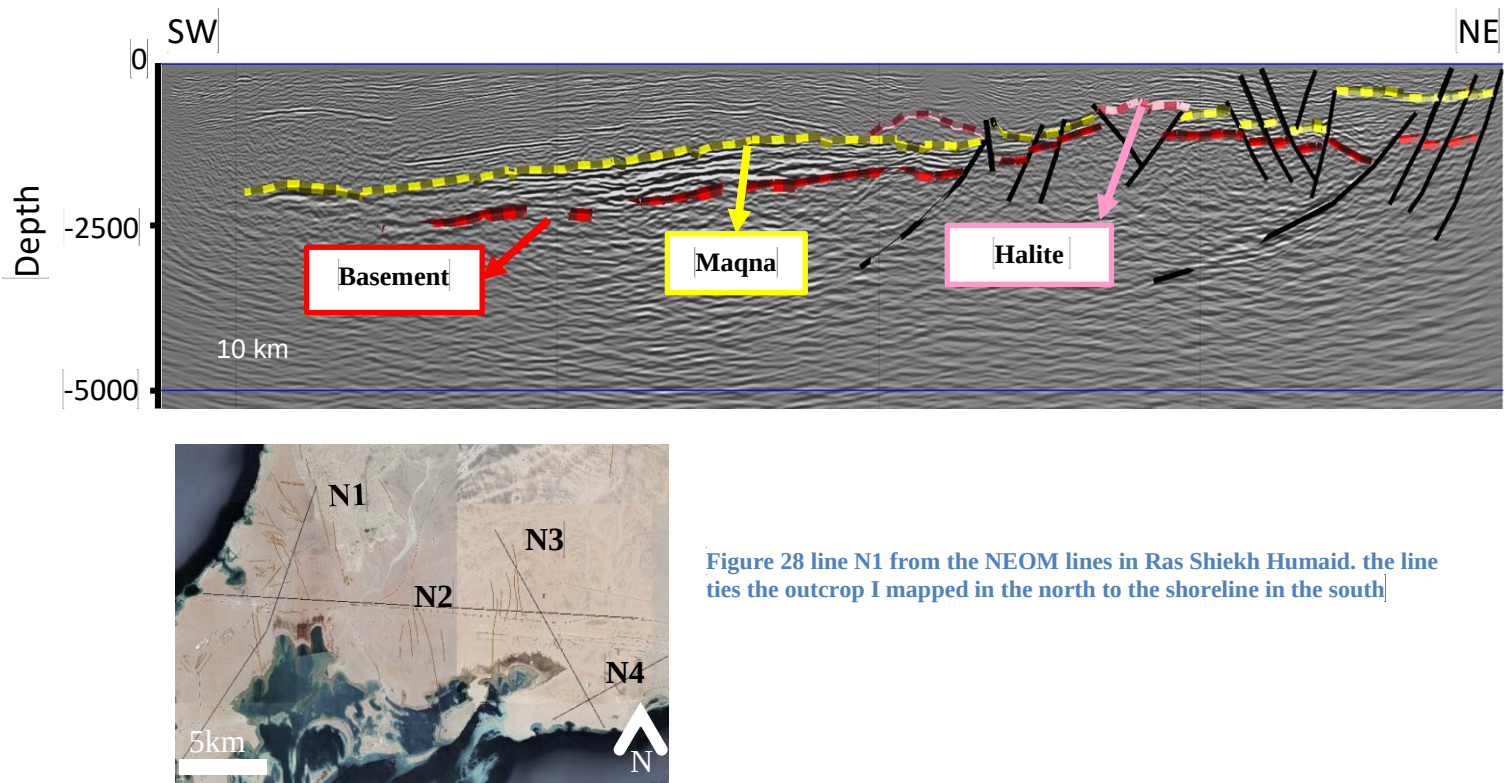
Neom has acquired several seismic lines in a recent campaign, allowing me to use 4 lines for this research. This data was processed with Kirchhoff PreStack time migration, post-processing processes, and lastly, time-to-depth conversion of the section.

The lines image the deepest portion of the basin in Midyan and offer insight into the connection between the rift faults imaged in the seismic lines published by Tubbs et al. and the surface strike slip faults picked west of the basin. This area is where I expect the strongest influence of the strike-slip system to be. In the satellite image (figure 26), you can see the regional east-west line and the north-south line in Ras Humaid cut through different major strike-slip zones, as evidenced by what I picked in the satellite image. This satellite pick correlates to faults evident in the seismic section, and the interpretation from both sources is consistent.



[Figure 27 satellite image with seismic lines from NEOM in black, and with surface faults posted in brown]

Line N1



In line N1, I see a series of sub-vertical faults at the northern tip that offset Maqna group to the surface. These faults are the same system I picked at the surface of the outcrop with sub-vertical beds (figure 28). This fault extends to link the offshore faults in the Gulf of Aqaba and extends to cut seismic line N2 and goes on to the offshore as one of the major fault trends in the onshore. Beyond that fault, most of the section in this area appears to have been a regional high as most of the formations appear to be thinner than they are regionally. This leads me to conclude that this has remained a regional high throughout most of the basin history and got down-dropped by the strike-slip recently to create accommodation space filled with Ghawwas/Lisan deposits.

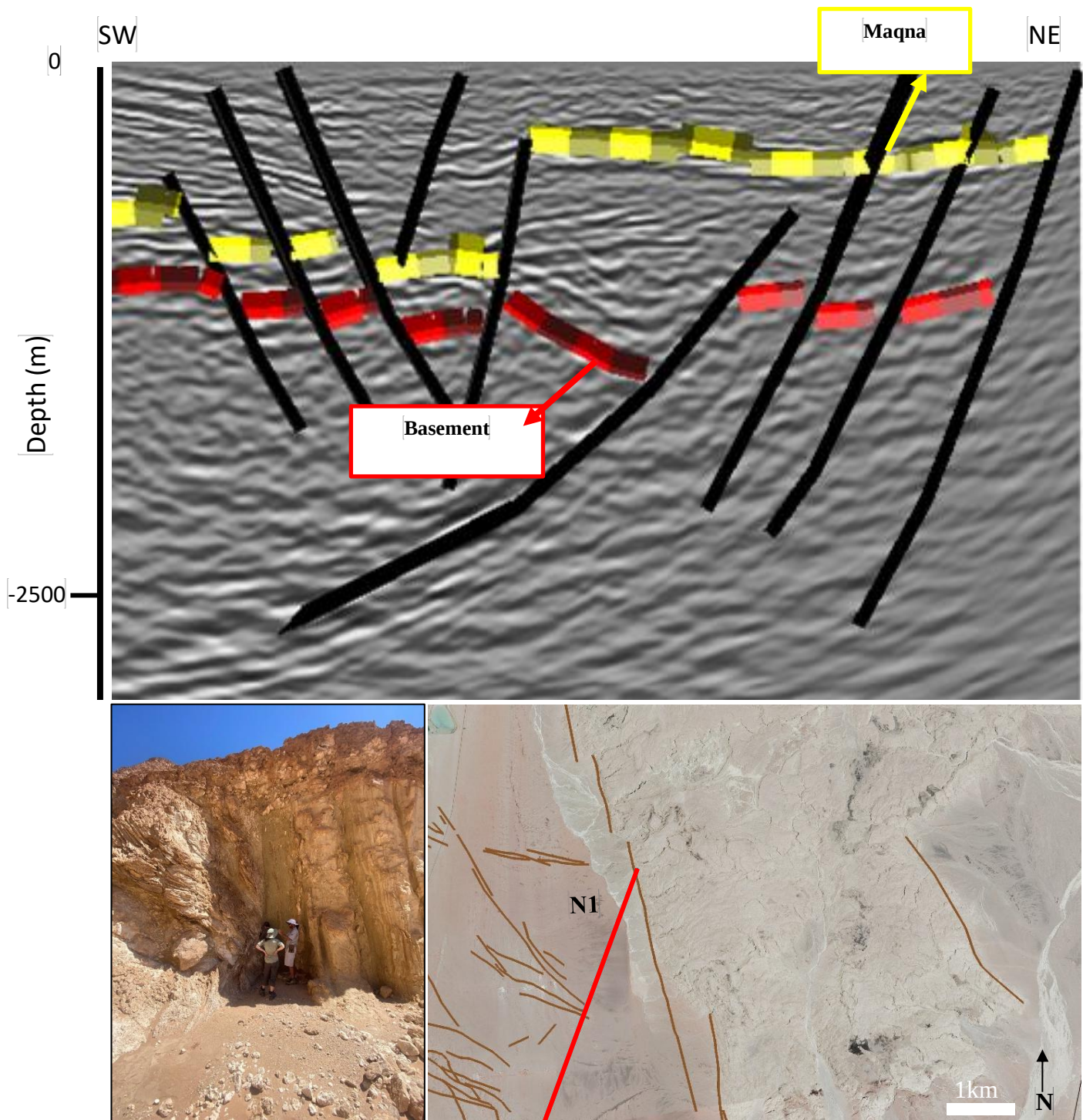
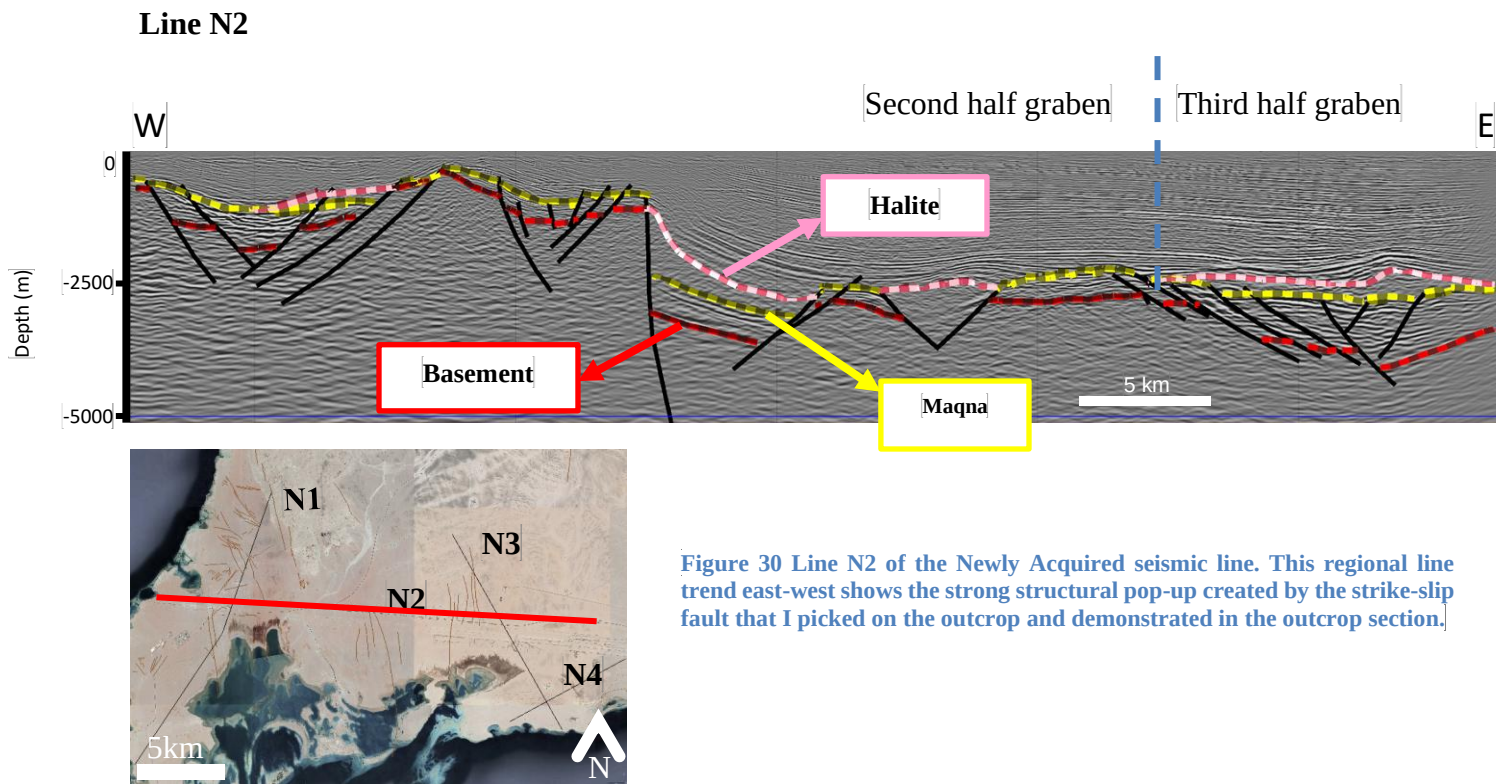


Figure 29 zoom in to the top of the seismic section on the northern end of line N1, and its location on the satellite image to show t it linking with the surface-picked fault



N2 line highlights the strike-slip structural control in the subsurface the most. We see that the basement drops along the strike slip almost 2 km in near vertical displacement. This pop-up structure is typical of large strike slip systems. Most of the displacement is filled with Ghawwas deposits and most of the salt has evacuated out from underneath it, most likely towards the sea. The thickness of the pre-salt section is not impacted much, which proves that this displacement got initiated and lasted through the Ghawwas time.

The basin structure makes 2 major steps in the seismic line as we move from the west to the east along the line. The first step that I discussed in the previous paragraph is due to the pop-up effect of the strike slip deformation, the second is towards the east of the line where we see significant change in the thickness of the pre-salt which indicates our crossing into the third half graben. This

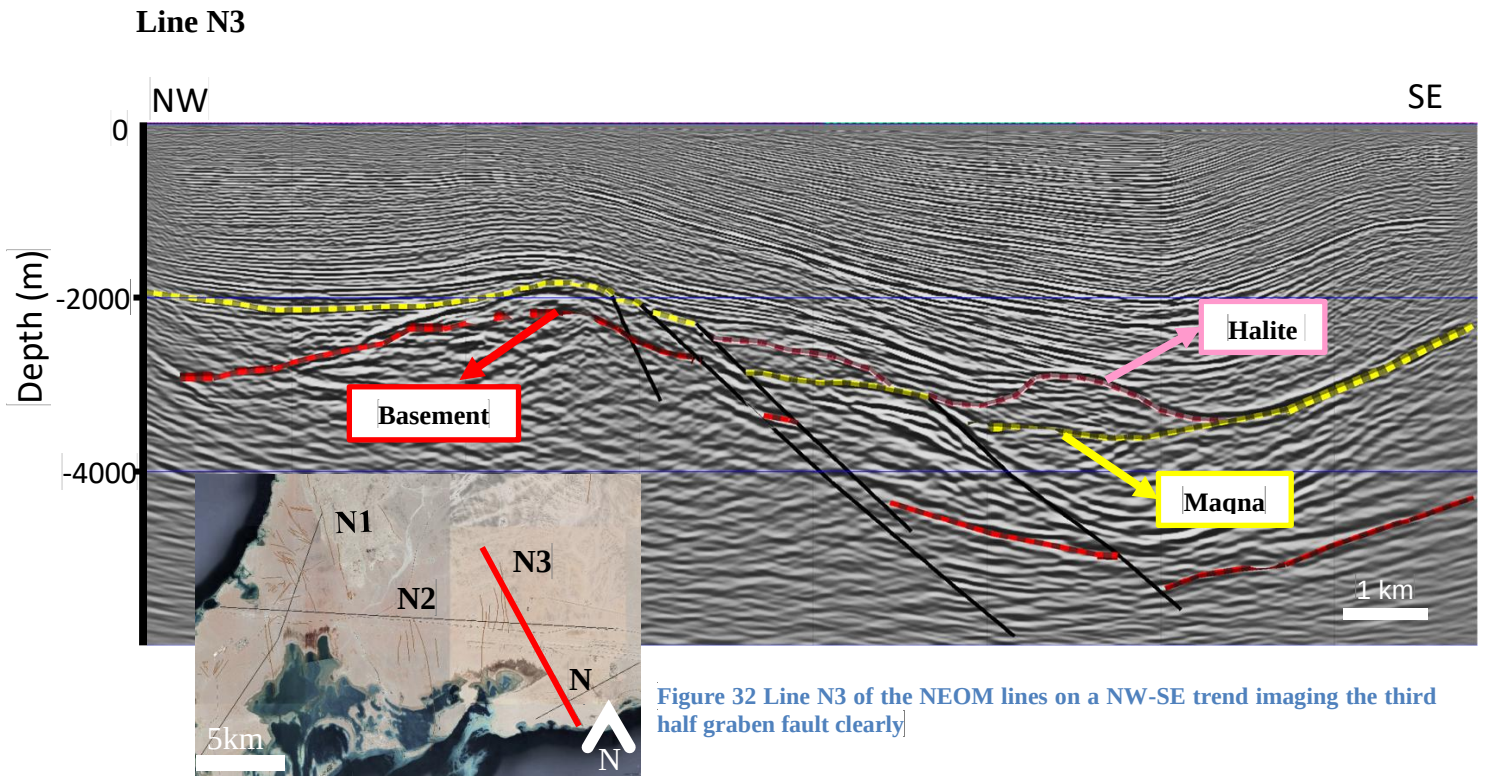
transition also shows a displacement of the base salt and some movement during Ghawwas deposition time. This is consistent with the observation made on the A-A' line from Tubbs et. al (2014) that I discussed earlier.

Salt evacuation direction

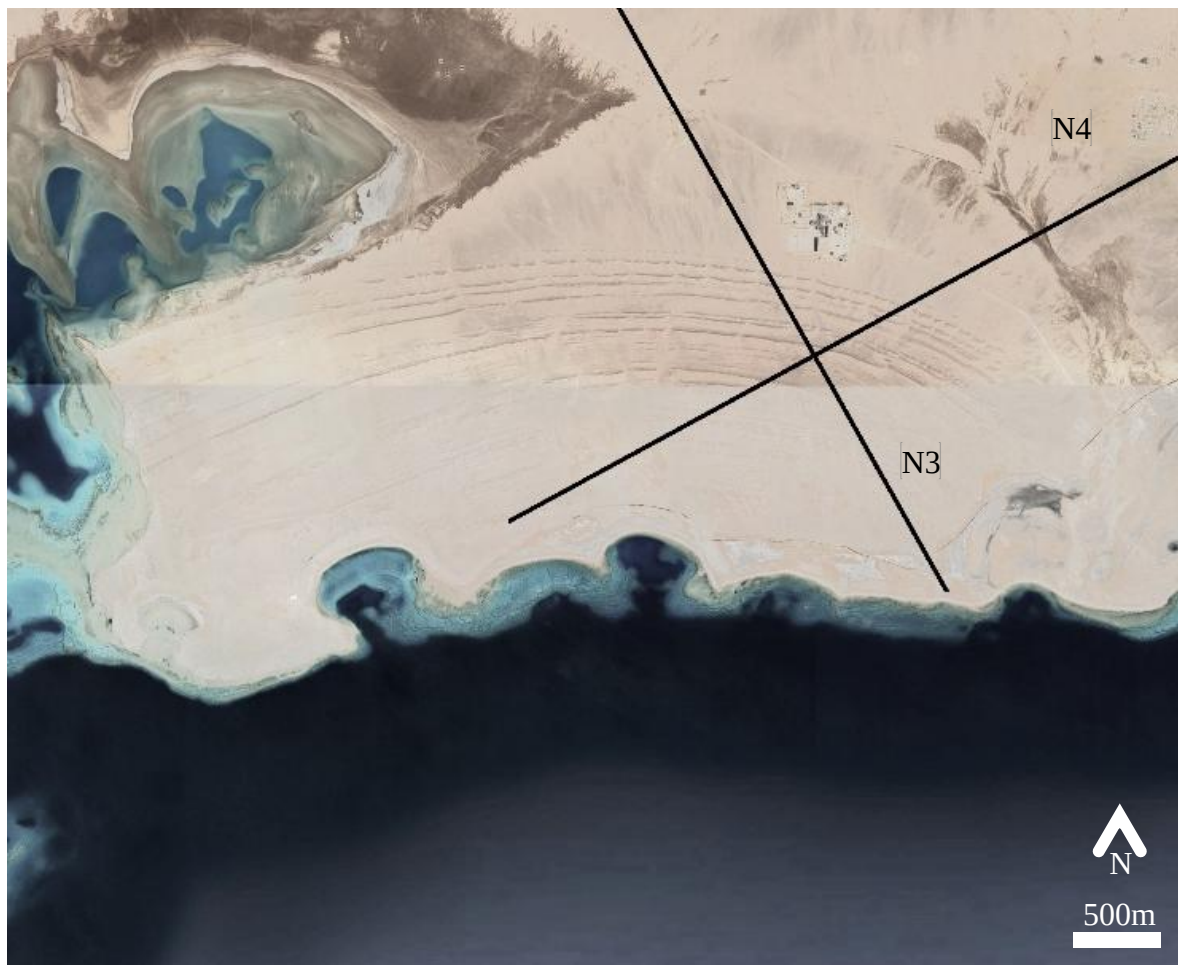
Salt evacuation towards the basin is supported by the observed offset of carbonate platforms toward the sea, as shown in the figure 31, is consistent with evidence of salt evacuation influencing platform deformation. Petrovic et al. (2023) describe how salt flow beneath carbonate platforms drives their fragmentation, rafting, and displacement toward deeper basinal areas. This lateral movement aligns with the direction of salt evacuation and reflects the interaction between salt tectonics and overlying carbonate systems. Such offsets provide a clear chronological framework of salt mobilization and platform response, supporting the interpretation that the displacement patterns in the Midyan region are a result of subsurface salt flow.



[Figure 31 satellite image showing evidence of salt evacuation towards the sea in northern red sea.]



Line N3 images the third half graben in a dip direction. The line clearly shows the continuous growth this direction has which demonstrated that the third half graben fault got re-activated as was indicated in line A-A'. we also see that most of the salt has evacuated and from the satellite image in figure 32 we can see that the direction of evacuation was towards the sea from the direction of the rings that are formed in the Ghawwas over burden. In this line we see that basement drops close to 5km below the surface, the deepest location in this area.



[Figure 33 satellite image showing the evacuation pattern in Ghawwas around the southern part of seismic line N3]

Line N4

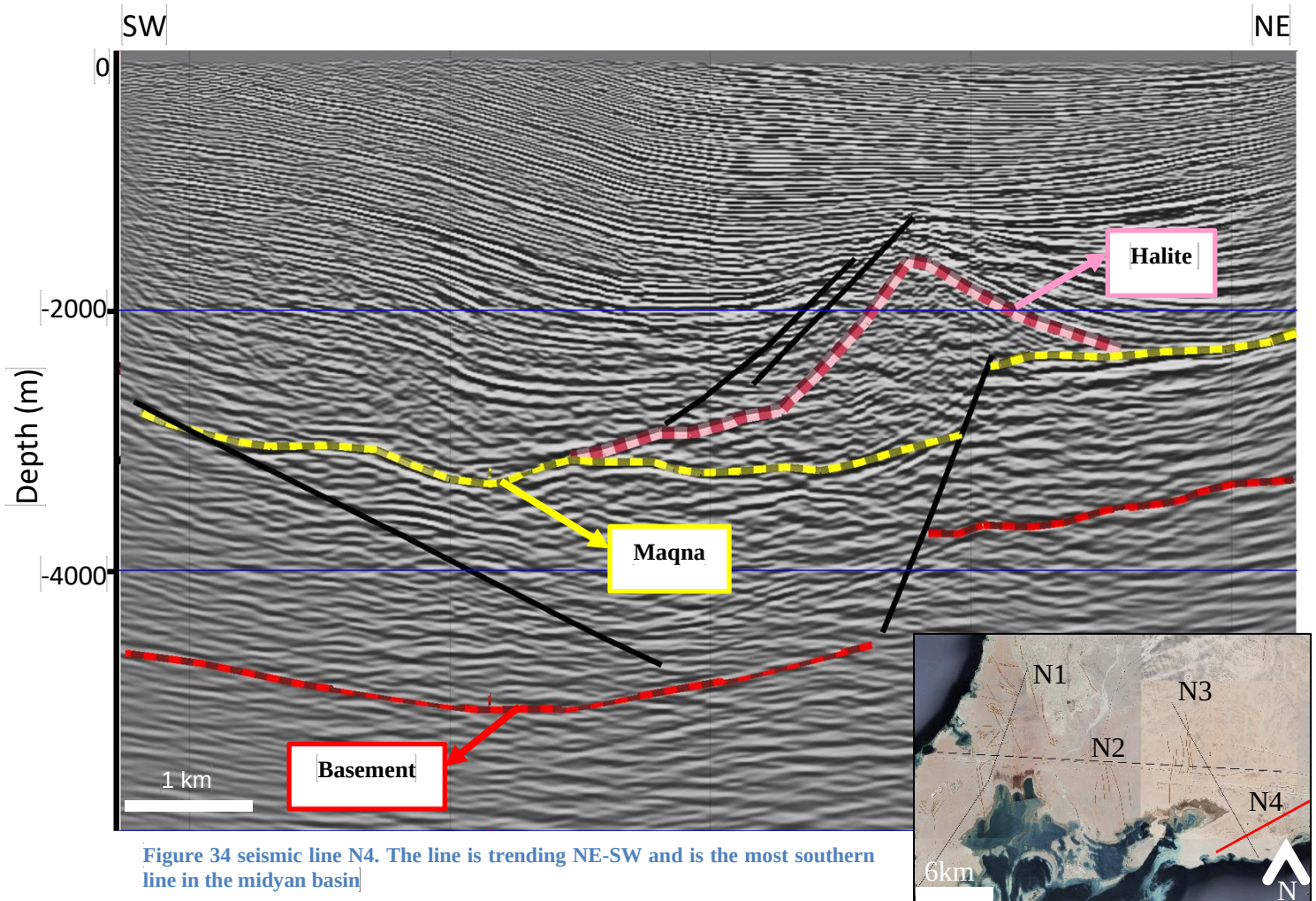


Figure 34 seismic line N4. The line is trending NE-SW and is the most southern line in the midyan basin

This line images the deepest zone in the study area which is within the third half graben. Most of the accommodation here is accommodated by the Ghawwas formation where it reaches a thickness of more than 3km. this indicates that this area (on top of being in the third half graben) has undergone significant subsidence during Ghawwas time as part of the gulf of Aqaba strike-slip system. There are indications of a fault in the seismic beneath the halite, and it's supported by the salt geometry and the welding pattern. The halite mobilizes until a weld develops around it and it

gets “stuck” with no where to go and stops. However, basement is clearly deep, reaching depths around 5 km based on this, and line N3.

4.1.4 Structural Model



[Figure 35 (left) all the available seismic we used. (right) picked faults in map view incorporating interpretation from seismic, outcrop, and satellite image. Strike-slip faults were picked in white, and rift faults are picked in black.]

To come up with the structural model for the Midyan area, I put all the data points together. To put the model together, I needed to pick the different major faults that shape the basin. The two major fault systems are the Red Sea faults and the Gulf of Aqaba strike-slip. These can be picked in combination from outcrop, satellite, and from seismic data.

It's important to distinguish between the different half grabens. As mentioned in the seismic interpretation, there are three different half grabens that get younger towards the basin. This starts with the first half graben in the back of the basin with its fault at the face of the mountain range forming Midyan basin's eastern margin and imaged well on seismic lines A-A' and B-B'. The

second half-graben is smaller, and its bounding fault is imaged in line A-A'. The third half graben is imaged in a number of the seismic lines, and most notably in line N3.

Picking the strike-slip faults includes picking the pull-aparts and delineating them into the surface picked faults. There are major faults that caused the uplift of the outcrops west of the Midyan basin that link up to the basin and can be imaged in the seismic. There're also major faults that are offsetting the Ghawwas anticlines that I used to link the interpretation in the different seismic lines.

The faults in Figure 32 in black are the confirmed rift faults, either picked in outcrop, or on seismic. The interpretation also fits published faults in Guillaume et. al and Matthieu et. al included faults in the offshore. There are different zones. Based on this I defined the different zones as in the Figure 36.

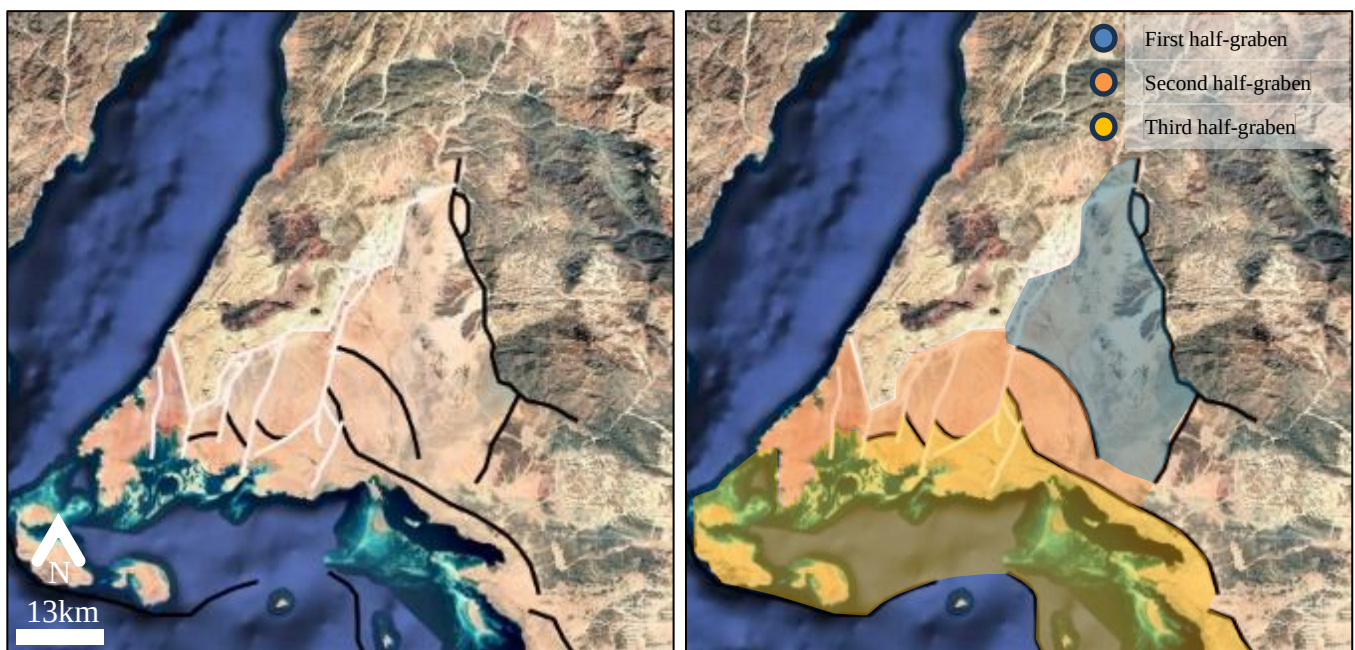


Figure 36 shows the different half graben zones and that's informative of what type of formations we should expect to encounter. The deposition sequentially started from in the half graben then deposition centered on the second half graben, then deposition finally shifted to the third half graben. The western side of the basin is cut up with different strike slip faults that significantly changed its geometry. One thing to note is that the second half graben is narrow, and generally the deposition thickness along it during the rift wasn't of significant thickness compared to other areas in the Red Sea. Also, the fact that there's no early rift deposits there might suggest that this area was a regional high through the basin history.

4.1.5 Basin Restoration

To restore the basin, I moved the coastline back to offset the rotation and displacement as published by (Delaunay, 2023). Putting the coastline back to close the Gulf of Aqaba places the Midyan basin in contact with the Sainai peninsula and links up the red sea with gulf of suez. To connect the displacement on both sides, I used the faults published by (Bosworth, 2005) and posted the faults I picked to see how they link.

To understand the basin history, and the change in depositional centers and how it relates to the regional story, I'm anchoring the displacement of the strike slip on the third half graben fault and closing the pull apart. For that restoration, I will create a block restoration by moving different blocks between the strike slip faults I picked to piece together the third half graben as a minimum displacement restoration.

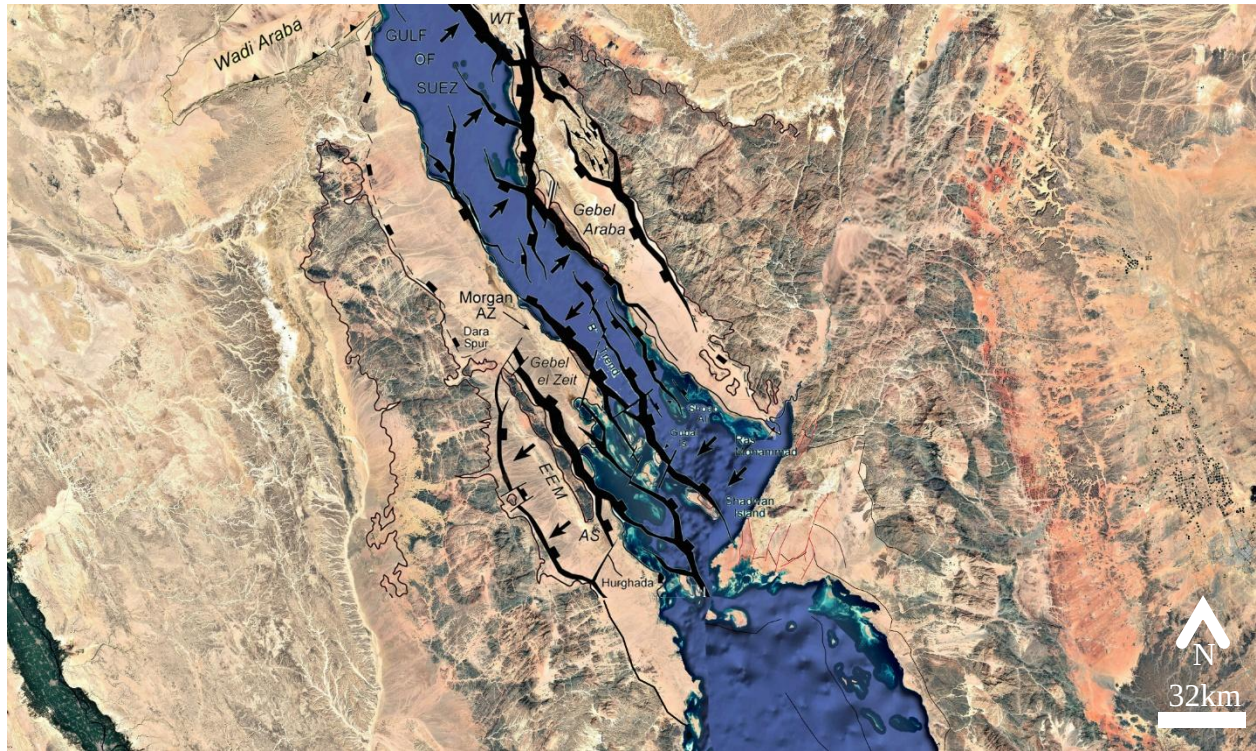


Figure 38 block restoration of the eastern red sea coast line to pre-Gulf of Aqaba transport and rotation to line up the rift faults and understand how the Midyan structure relates to the gulf of Suez right north of it. This block restoration was done based on work published by (Delaunay, 2023).

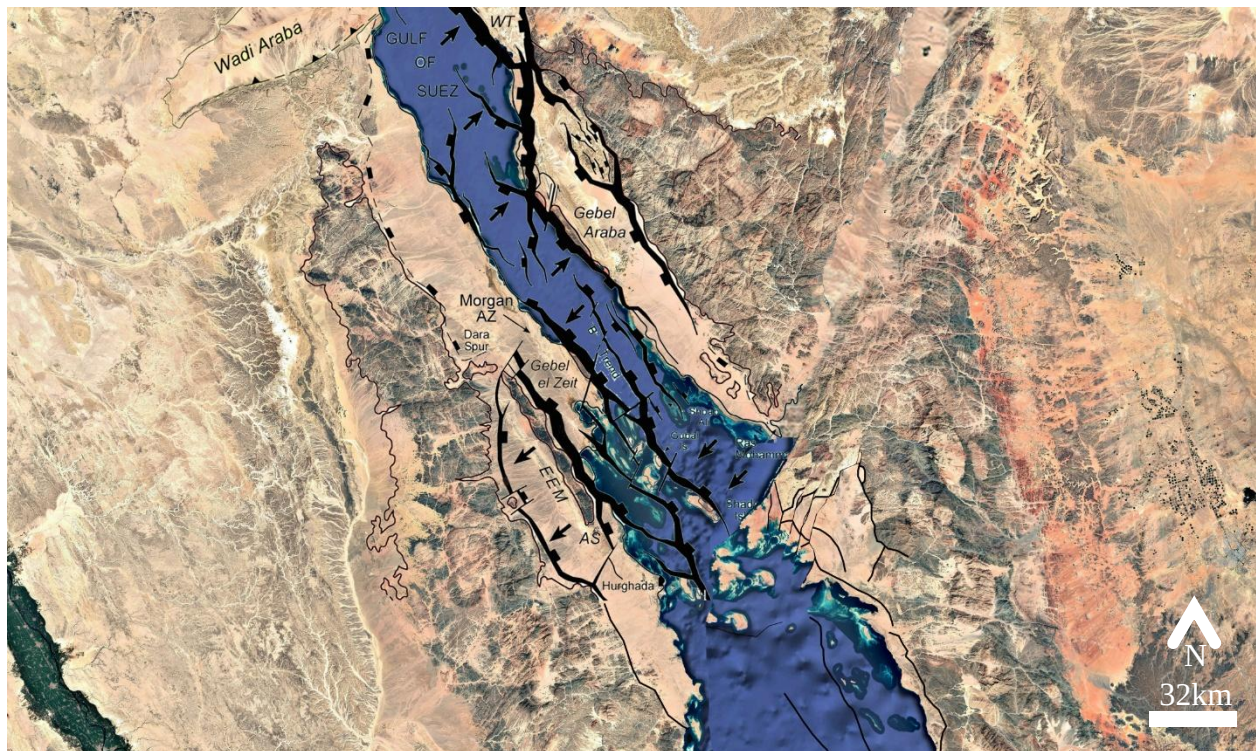


Figure 37 restoration of the minimum onshore displacement along the individual picked major strike slip displacement faults to restore the third half graben fault to its position

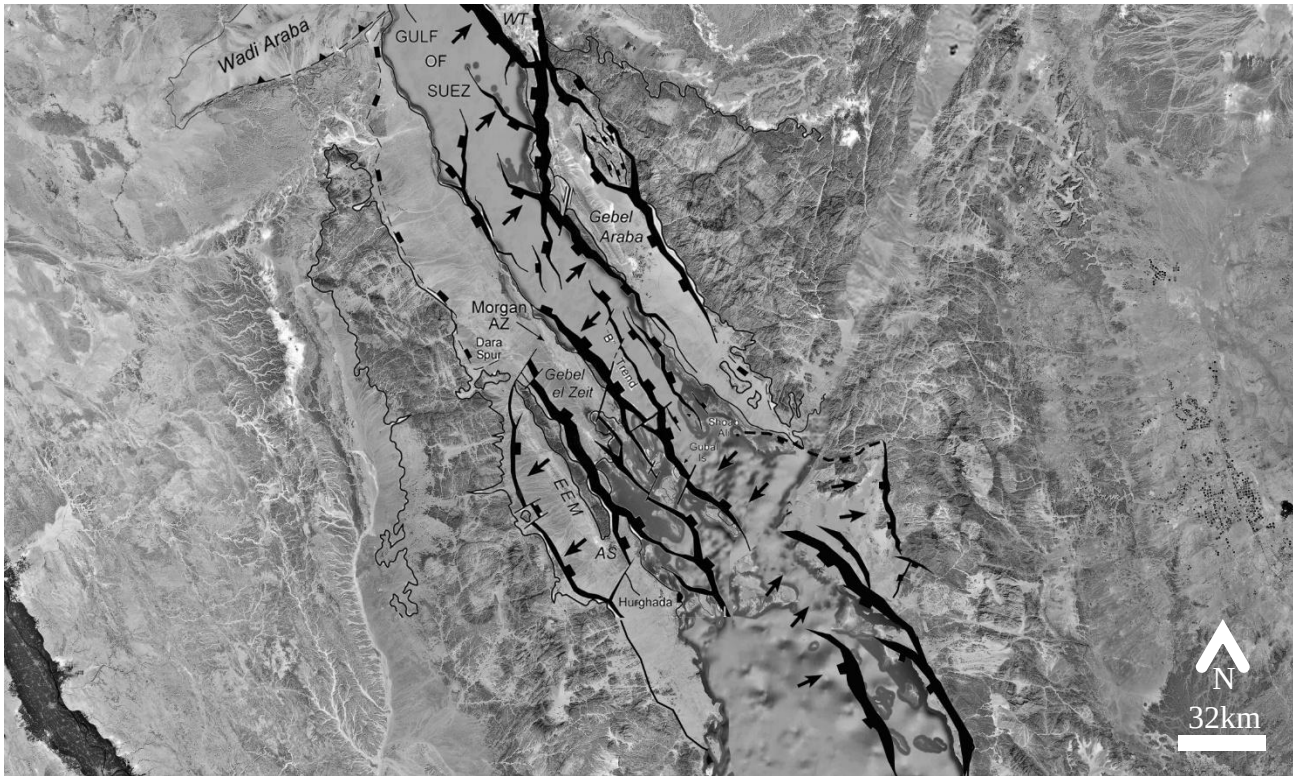


Figure 39 Restored section showing the rift faults on both side of the northern Red Sea and Gulf of Suez prior to the initiation of the Gulf of Aqaba fault system. The section involves interpretation done as part of this work, merged with interpretation published

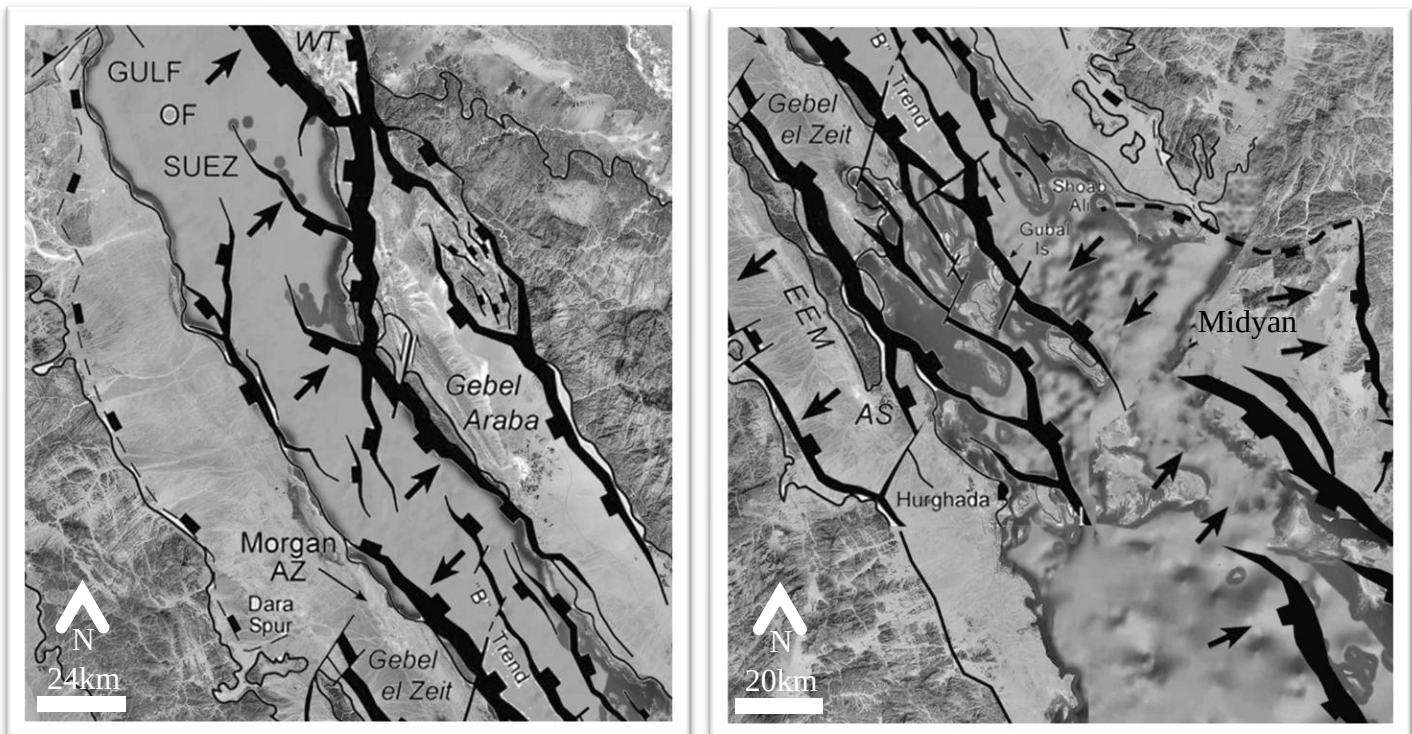


Figure 40 (left) zoom into the Morgan accommodation zone in Gulf of Suez where the polarity of the half graben faults flip between the north and south from west dipping to east dipping faults, respectively. (right) the Midyan area where I'm proposing another accommodation zone where the polarity flips from east dipping to west dipping fault from north to south.

The northern Red Sea and the Midyan area are characterized by west-dipping rift faults that form a series of half-grabens, creating the primary sedimentary basins in the region. Restoration work reveals that the northern part of the Midyan area, where the Gulf of Aqaba was initiated, represents a zone of polarity flip. This is evident when comparing the southern Gulf of Suez, where the half-graben faults dip eastward. This polarity flip indicates that the region likely functioned as an accommodation zone within the asymmetric rift system, analogous to the Morgan accommodation zone in the southern Gulf of Suez. This structural interpretation is further supported by the relatively thin sedimentary deposition observed in the second half-graben. The onshore area likely served as a cross-basin arch, remaining a regional high throughout the early and late phases of the Red Sea rift. This high was eventually down dropped during the propagation of strike-slip faulting, leading to the formation of localized upthrown and down blocks, which along with the lateral translation further reshaped the region's structural configuration.

4.2 Conclusion

This study provides a comprehensive structural interpretation of the Midyan Peninsula, integrating seismic, satellite, and outcrop data to unravel its complex tectonic history. The results reveal a multi-phase tectonic evolution involving west-dipping rift faults, salt tectonics, and strike-slip deformation. The identification of a polarity flip in the northern Midyan area, analogous to the Morgan accommodation zone in the Gulf of Suez, underscores the role of the peninsula as a transition zone within the Red Sea rift system. The basin's history of salt mobilization and strike-slip faulting is reflected in the offset of carbonate platforms and the formation of distinct structural highs and lows. By linking

these features to regional tectonic processes, the study enhances our understanding of the interplay between rifting, salt tectonics, and strike-slip deformation in shaping the northern Red Sea. Future research can build on these findings to further refine the tectonic model and explore its implications for resource exploration and seismic hazard assessment.

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