GRC Transactions, Vol. 48, 2024

Exploration of Deep Hot Sedimentary Aquifer Geothermal Systems in The Midyan Basin of Saudi Arabia by ENOWA-NEOM

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Keywords

Geothermal, Hot Sedimentary Aquifer, Midyan Basin, Saudi Arabia

ABSTRACT

This study was conducted to investigate the potential for a hot sedimentary aquifer geothermal system within the NEOM area in the northwest of Saudi Arabia using regional geophysics and 2D seismic lines covering the main known basins along the Red Sea coast. The thickness of each basin was investigated to determine the maximum depth to basement within each basin. The Red Sea sedimentary basin deposition started as part of the Red Sea rift sequence and is mainly influenced by tectonic activity within each subregion of the early rift. The Red Sea rift began ~32 Ma and has created the basin that includes the modern-day Red Sea and the Gulf of Suez. The rift presents itself as a series of half grabens that extend from Bab Al-Mandab Strait in the south to the Mediterranean in the north. This tectonic arrangement was superimposed in the northern Red Sea by the strike-slip tectonics of the Gulf of Aqaba in which began movement ~12 Ma as part of the left-lateral Dead Sea Fault system.

This is the first attempt at geothermal exploration in these sedimentary basins, where currently no known systems exist. The basis for designing this exploration work is on the premise of conduction heat flow, with no impact of convection or magmatic processes that would diverge away from the background heat gradient. Using the known heat gradient in the area from oil and gas wells, the intent is to drill into a reservoir at a depth that delivers the necessary temperature for use as geothermal power, heating, and refrigeration. Using a greenfield exploration approach, the workflow has included the analysis of regional geology, heritage well data, published technical papers, geologic map data, 2D imagery, airborne magnetic and gravity data, along with the acquisition and interpretation of 180 km of 2D seismic. Of the mapping completed thus far, several targets were identified in the Midyan area where the investigation suggests deep basins which could host Hot Sedimentary Aquifer geothermal systems. The targets in the area lie in syn-rift sedimentary reservoir-seal pairs that are deeper than 3 km at present and are either within marine

turbidite sands, or early-rift continental sands capped by marine shales. The 2D seismic interpretation along with the assessment of other existing data will form the basis of discussion as to how the identified prospects were chosen.

1. Introduction

NEOM is the planned independent economic zone in the northwest of Saudi Arabia. It is born out of the ambition of Saudi Arabia's Vision 2030 to see the country develop into a pioneering and thriving model of excellence in various important areas of development. ENOWA is a 100% subsidiary of NEOM that is tasked with delivering NEOM's energy related vision to life. This vision is to become the world's most advanced renewable energy hub and the first at-scale fully renewable electrical system. NEOM aspires to have a high degree of electrification, which results in increased electricity requirements compared to traditional economies. To provide affordable renewable electricity, ENOWA aims to develop geothermal resources.

One of the main geothermal plays in development in the NEOM region is the hot sedimentary aquifer (HSA) geothermal system within the Midyan Basin. This is the first attempt at geothermal exploration in these sedimentary basins, where currently no known systems have been proven to exist, nor has geothermal infrastructure been established. This paper will discuss the exploration of the Midyan Basin's potential to host a hot sedimentary aquifer geothermal system from the standpoint of both existing and acquired geophysical data, and the identification of potential geothermal prospects that have resulted from the assessment.

2. Available Data

2.1 Published Regional Work

While there are not yet any published works about the NEOM development specifically, regional studies of the larger Red Sea and Midyan Basin areas have assisted in creating the framework and context of the depositional and structural history of the basin. Published geophysical studies of the area have also provided a baseline for the planning and expectations of further surface exploration.

2.1.1 Regional tectonic history

Bosworth (2015) provides a detailed description of the geological evolution of the Red Sea, along with Hughes & Johnson (2005), which in turn provides a detailed account of the lithostratigraphy of the Red Sea Region. These regional studies guide our understanding of the tectonic history of the Midyan Basin region and provide detailed information on the different lithological units that exist within the larger basin. The lithostratigraphy of the region is described in further detail in Section 3.3.

2.1.2 Regional magnetics and gravity

Regional gravity and magnetic data are available from SGS Saudi Arabia. This dataset was interpreted and used in choosing the locations of the 2D seismic lines for the seismic field study as described in sub-section 2.4. It is also used to de-risk the seismic interpretation by linking the newly acquired 2D seismic lines to the non-seismic surveys.

2.1.3 Published seismic profiles

In 2014, Tubbs et al., through one of the Saudi Aramco geologic field programs, acquired onshore 3-D, transition zone 2-D and offshore 2-D seismic data in the Midyan Basin to provide further insight into the geological history of the region. This study provides a detailed assessment of the structural interpretation of the Midyan Basin, along with a lithostratigraphic and seismic stratigraphic interpretation of the Midyan area.

2.2 Outcrop Geology

The surface geology of the NEOM area is based on a regional geological map of the NEOM area. Supporting surface geological interpretation includes satellite imagery maps and structural maps that have assisted in mapping structural faulting and observable lineaments.

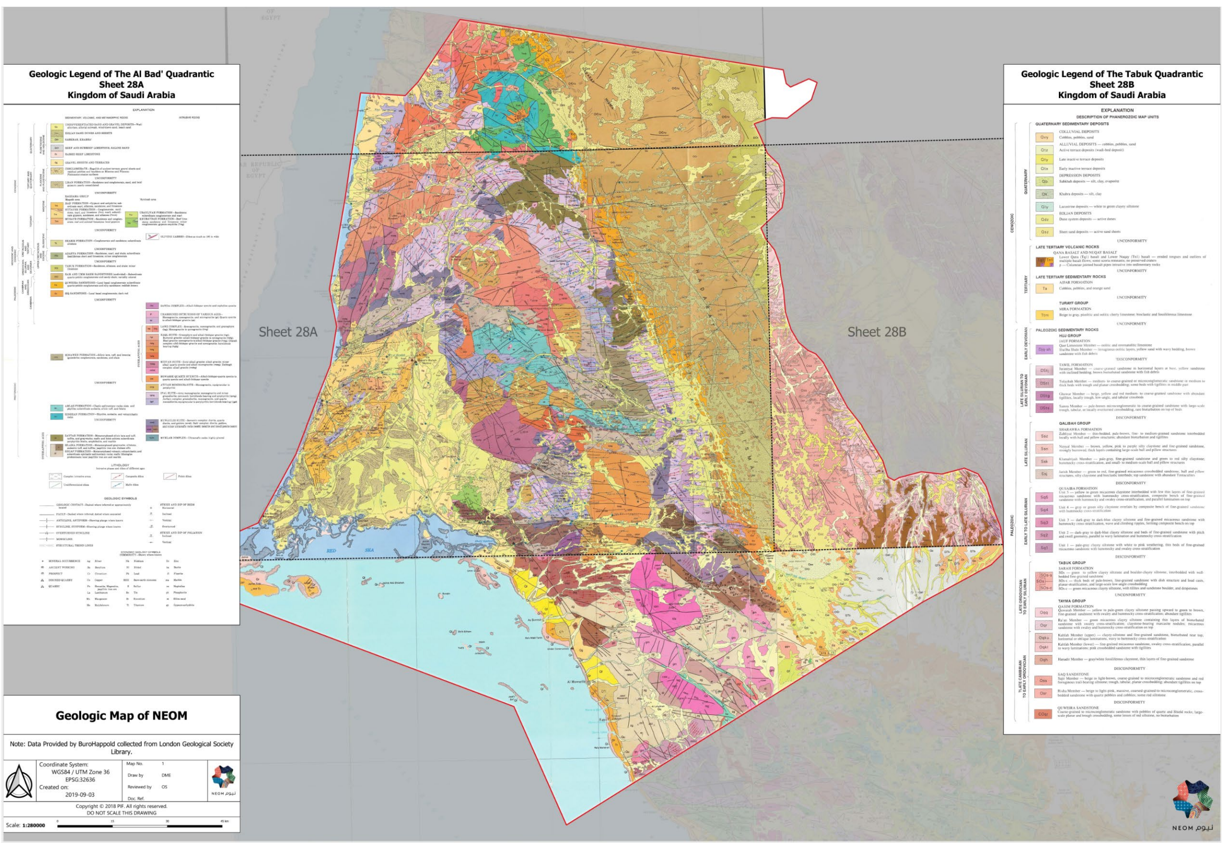

Figure 1. A regional surface geological map of the NEOM area. A more detailed regional context is provided in figures 5 and 6.

With these maps as a basis for field exploration, evidence of late Quaternary faulting was investigated during a field visit in August of 2022. From what was observed, it is thought that scarps found in the field were possibly associated with recent faulting and salt movement.

2.3 Legacy Well Data

Temperature surveys from 5 shallow (< 3000 m total depth) oil and gas wells drilled in the Midyan Basin were obtained. Measured temperatures in these wells reveal conductive geothermal gradients between 30-35 °C/km.

Limited information from shallow water wells that have been drilled in the area were also obtained, with majority of the wells drilled in the area of Tabuk, which is a town directly northeast of the border of the NEOM area. The wells that were drilled in Tabuk reach up to 600-1250 m in depth, and temperatures around 40 °C.

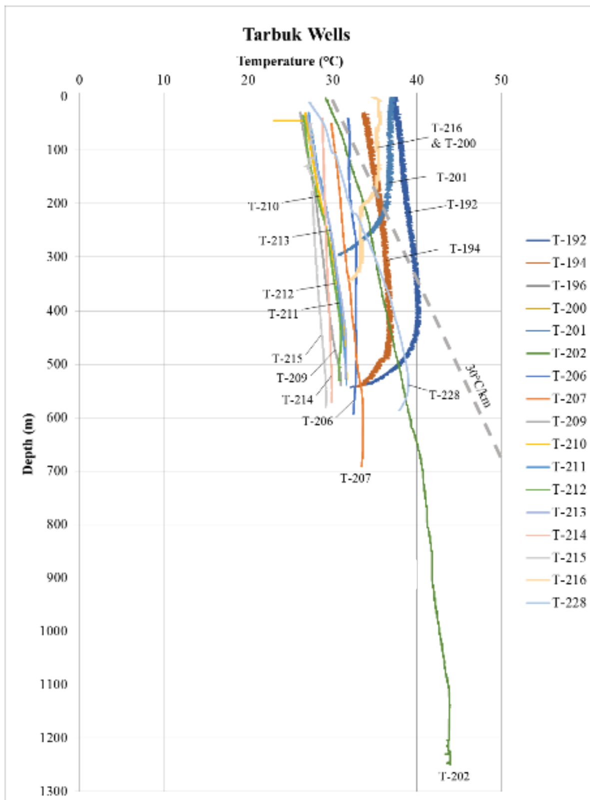

Figure 2. Temperature of water wells drilled NW of the town of Tabuk, directly NE of the NEOM area.

In addition, 1201 shallow geotechnical boreholes have been drilled along the western coast of Saudi Arabia and along the eastern shore of the Gulf of Aqaba. These wells do not surpass a depth of 60 m and present information of the shallowest formations in the area.

2.4 Newly Acquired 2D Reflection Seismic Data

As part of the study to identify areas of potential geothermal resources, 15 (fifteen) 2D onshore seismic lines were acquired in 2023 in the NEOM area to gather detailed subsurface information, characterize the reservoir, identify structural features and reduce exploration risks. The seismic survey reached a total length of 180 km. The results of this seismic field survey helped identify the Midyan Basin as one of the main areas of interest for hot sediment aquifer exploration. The processing sequence follows a full production Pre-Stack Time Migration (PSTM) sequence to improve the overall structural imaging and resolution.

Figure 3. The locations of the seismic profiles in the Midyan area of the seismic survey of March 2023.

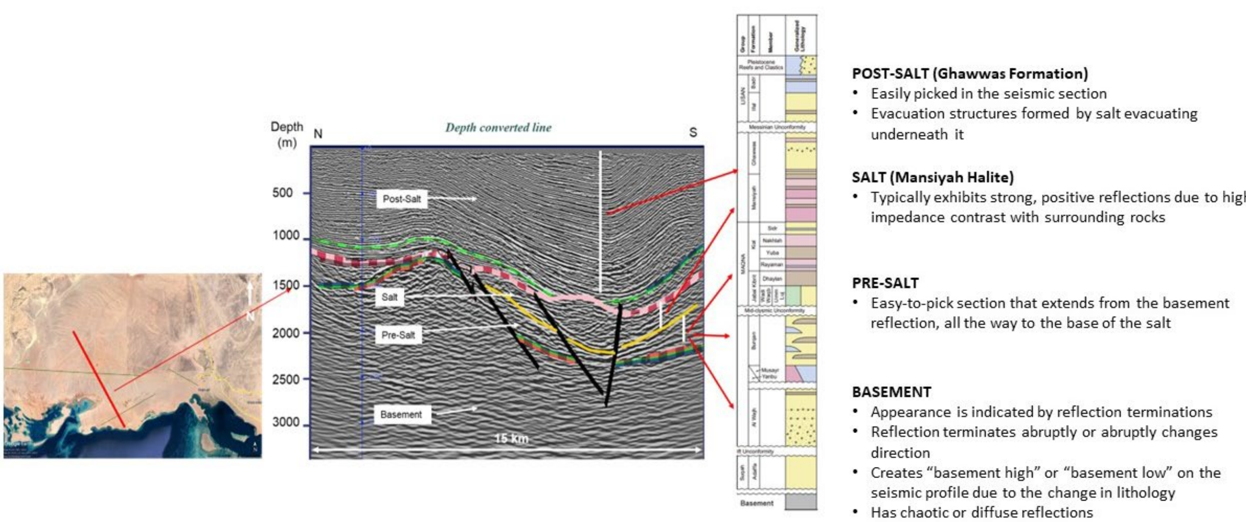

Figure 4. An example of a seismic line and interpretation from the 2023 seismic survey conducted in the NEOM area.

3. Regional Geology and Structural Style

3.1 Regional Geology

The regional area of interest is in the northwestern part of Saudi Arabia, directly northeast of the Red Sea Basin, which is a divergent plate margin. The Red Sea basin was formed by a continental rift that started 30-32 million years ago by initiation of the Afar Plume (Figure 6-a and -b) (Bosworth, 2015), and eventually developed into an oceanic rift that now hosts the Red Sea, and forms part of the boundary between the African and Arabian plates. The Red Sea basin started as an asymmetric rift that propagated from the south to the north in a series of deep half grabens all along the Red Sea. At the beginning of the rift, the Gulf of Suez was considered part of the Red Sea and shared the same history and structural trends. All along the Red Sea basin, there are several zones of half grabens that dip towards the Arabian plate, and others that dip towards the African plate with accommodation zones in between associated with oblique cross-basinal arches. These have been studied in detail in the Gulf of Suez and have also been demonstrated along the main Red Sea.

Pre-Miocene formations are considered to predate the development of the rift. Cretaceous formations are the oldest in the section, and are thickest within Gulf of Suez, and thin towards the south until they disappear offshore and in outcrop (on the Saudi Arabian side) within the northern areas of the Red Sea (Adaffa and Usfan Formations; Hughes, 2005). Some Cretaceous outcrops are preserved with down dropped basin grabens in outcrops within the NEOM area (e.g., Adaffa Sandstone Formation). There are some other Cretaceous outcrops preserved within grabens along the Saudi coast that extend to the south, nearly reaching the Yemen border.

The early stage of the rift resulted from rift-normal extension that is postulated to have opened the whole 2,200 km long Red Sea simultaneously (Figure 6-c) (Bosworth, 2015). At this stage, the Early Oligocene rift deposits were the continental sands of Al Wajh formation, which are present everywhere in the Red Sea as continental red beds and lacustrine deposits that reach up to 2200 m in thickness. This was followed by a marine incursion that deposited the deep marine turbidites of the Burqan formation where the rift was most active tectonically; in these areas the Burqan is the thickest formation.

A change in depositional environment is marked by outcrops revealing the intra-Burqan mid-clysmic unconformity (~17.5-18Mya) that ended the deposition of the Maqna group (Figure 8) (Tubbs et al, 2014). The Maqna group shows clear signs of low tectonic activity and of basin wide restriction where several regional anhydrite formations, interbedded with clastic and carbonate formations, were deposited. The basin restriction developed into a basin wide salinity crisis linked to the Mediterranean Messinian restriction, and the Red Sea that deposited the massive Mansiyah halite (Gargani, 2008).

Around 14-12 million years ago, the Gulf of Aden rift developed into an oceanic ridge with seafloor spreading and the Arabian and the Eurasian plates collided, rotating the Arabian plate around a north-African Euler pole counterclockwise and causing the Red Sea to switch to a rift-oblique extension (Figure 6-d) (Bosworth, 2015). The new shift in extensional direction caused reactivation of some faults, and strike-slip deformation as the faults moved to accommodate the differential extension.

The opening of the Gulf of Aqaba in the Late Miocene (5-12 million years ago) occurred after the Red Sea Rift had already stopped its initial rifting (~14 million years ago). Its opening helped accommodate the plate rotation, and the extension along the Gulf of Suez was abandoned, making it a dead rift. This also created late strike-slip deformation across the basin especially in the northern Red Sea and within the Midyan peninsula, creating pull-apart basins and further deepening the basin as a whole.

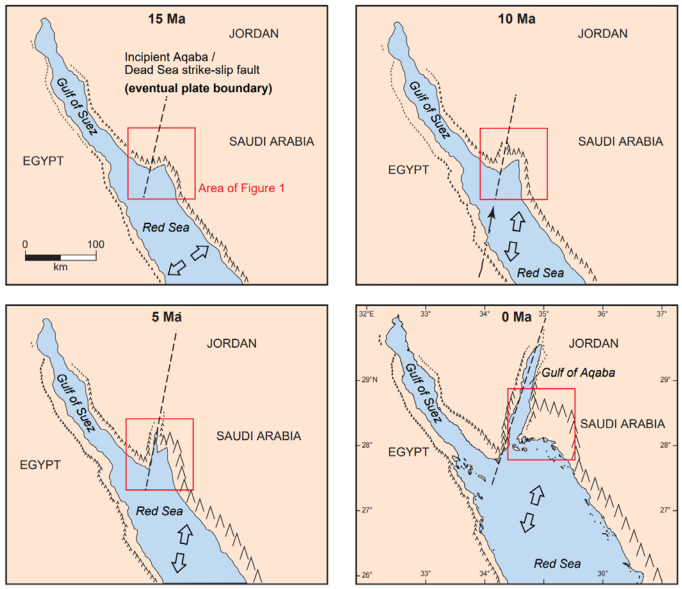

Figure 5. A schematic of the opening of the Gulf of Aqaba as illustrated by Tubs et al. (2014)

The Red Sea changed into a drift regime with the extension localized to the center of the Red Sea while the plate moved along the Aqaba strike-slip system to reach a total left-lateral displacement of 107 km (Quennell, 1959). The southern end of the Red Sea opened an extra 26 km due to the plate rotation. The combined displacement caused several pull-apart basins along transtensional bends to develop. The Gulf of Aqaba Sea is one large pull apart basin separating the Sinai Peninsula from the NEOM region.

Around 5 million years ago, seafloor spreading initiated in the southern Red Sea, and a ridge formed that transferred most of the deformation to the center of the sea (Figure 6-f). Continental rifting ceased in the south and only localized deformation continued offshore in the north.

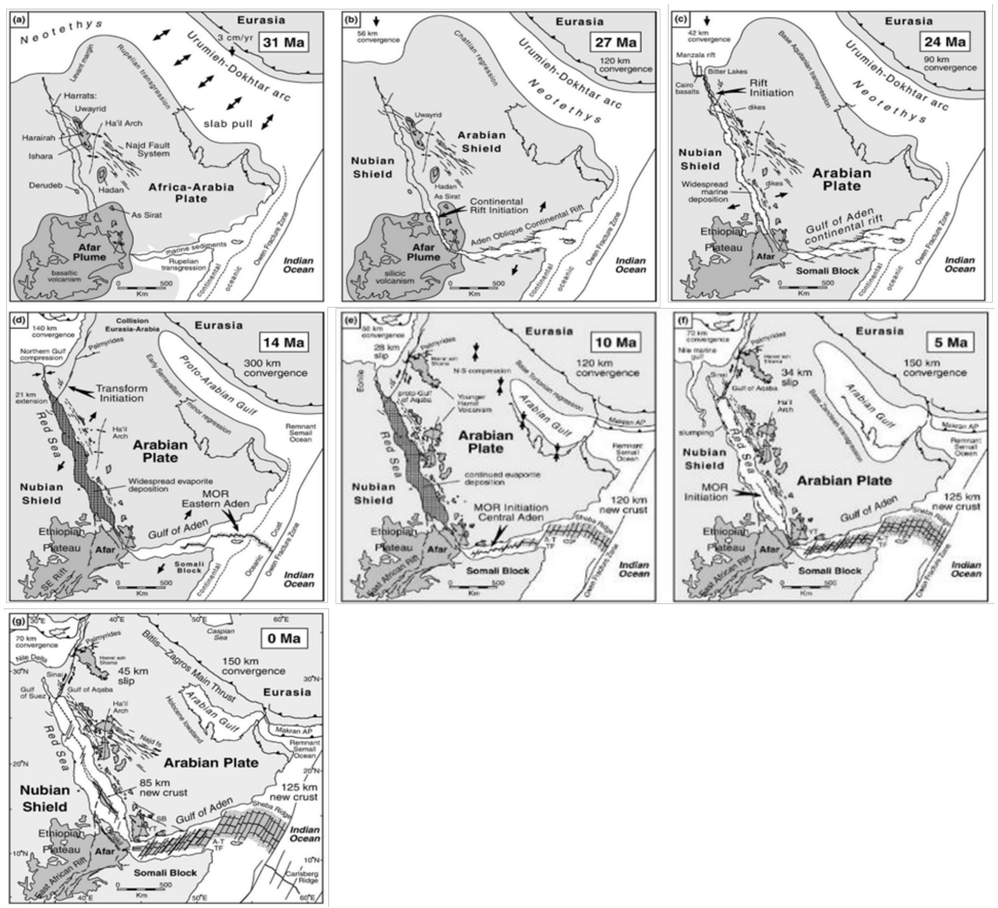

Figure 6. The evolution of the Red Sea rift from the initiation of the Afar plume, through the rift climax, strike slip initiation and rotation axis change, and to modern day system. (Bosworth, 2015)

3.2 Regional Structural Setting

The Red Sea developed as an asymmetric rift associated with oblique extension starting in the Oligocene through Late Miocene. A schematic of an asymmetric rift system can be seen in Figure 7-a. Under transtensional strain, a geometry of half grabens bounded by synthetic faults formed across the width of the basin (Figure 7-b). The dip polarity of the half grabens flips in several regions of the Red Sea and Gulf of Suez at several transfer zones from east- to west-dipping and west- to east-dipping. These transfer or accommodation zones link the displacement across regions of the sea and represent cross-basinal arches where dip directions rotate. The regional structural framework can help guide exploration by adding context to rift geometry at subregional scale.

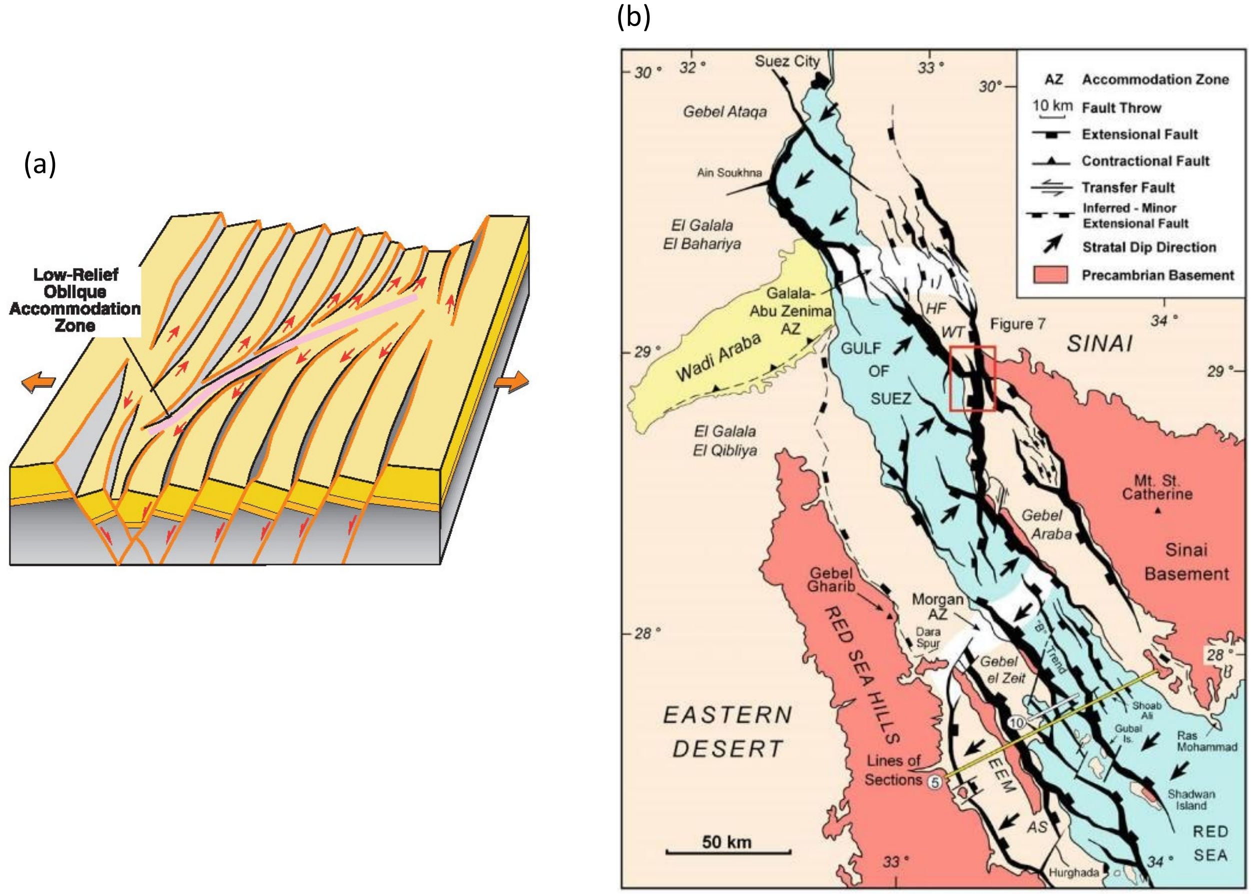

Figure 7. (a) Schematic of the transfer zone in asymmetric fault systems from a sandbox experiment. (McClay, 2002) (b) Faults in the Gulf of Suez with different transfer zones labelled. (Bosworth, 2005)

3.3 Stratigraphic Framework

The Red basin stratigraphic section is dominantly related to the tectonic history of the Red Sea rift. Overall, the pre-rift section is thin, and the rift sequence is often directly overlying crystalline basement. Therefore, a clear character to defining the stratigraphic section is in relation to the rift stage. This is especially useful because the kinematics of the rift itself are the largest influence on the depositional environment, as well as the basin shape and accommodation space. Hence, the section can be divided into a pre-rift, syn-rift, late rift, and post-rift. These must also be contextualized within the overall understanding of the space creation within the different zones of the Red Sea, the fact that the faults along the rift margin are no longer active, and the plate motion is accommodated by space creation offshore. There are several hypotheses related to the onset of the ocean crust formation, as well as hyper-extension of the offshore continental crust. The method in this report by which we define the rift formation relates to the rift fault kinematics onshore. The understanding of the onshore basin is calibrated by published literature on the onshore drilling results, and outcrop studies.

There are 6 formations that are a major part of the Red Sea Basins. From youngest to oldest, these formations include:

1. Ghawwas Formation (~12 to ~6 Ma)
   The Ghawwas formation is a post-salt formation dominated by sandstones with minor intercalated carbonates deposited within salt mini-basins controlled by accommodation space within the halite body.

2. Mansiyah salt formation (15.3 to ~12 Ma)
   The Mansiyah formation is a massive halite deposition formed during a basin wide salinity crisis that can be linked to the Mediterranean Messinian restriction. This formation acts as a regional marker in the area.

3. Maqna Group (17.5 to 15.3 Ma)
   The Maqna Group is a pre-salt formational group comprising interbedded fine to medium-grained clastics and carbonates that was formed during a period of low tectonic activity and basin-wide restriction.

4. Burqan Formation (20.5 to 18 Ma)
   The Burqan is a pre-salt deep marine turbidite that was deposited by a marine incursion.

5. Al Wajh Formation (33 to 21 Ma)
   The Al Wajh is a pre-salt high porosity sandstone formation that was deposited during the earliest stage of the rift.

6. Neoproterozoic Basement
   There is an unconformity present due to the transitional zone between the sedimentary units and the Neoproterozoic granitic basement. It is of note that the basement can also potentially host permeable faulting, below the sediments, however the nature of these faults has not yet been studied in depth.

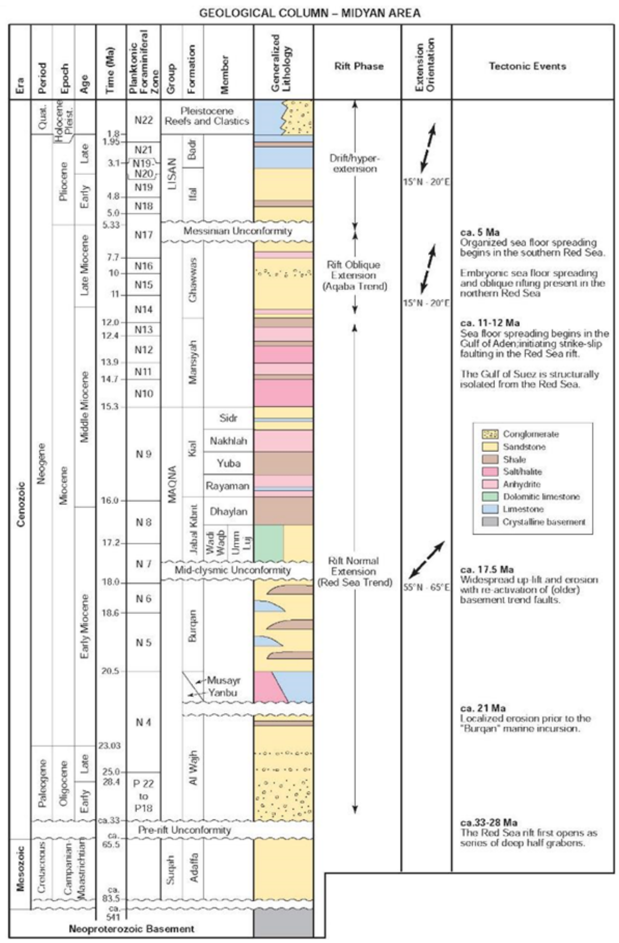

Figure 8. Generalized lithostratigraphy of the Midyan Basin.

4. Geothermal Workflow and Results

From the data presently available, the Midyan Basin has been assessed using a greenfield exploration approach, while under the assumptions associated with a hot sedimentary aquifer (HSA) play. In an HSA geothermal play, the reservoir is heated by conduction with no impact of convection or magmatic processes that would diverge the reservoir temperature away from the background heat gradient. The temperature that would need to be reached for geothermal commercial purposes would thus be a function of depth and background gradient. The permeability of the subsurface is below the convective threshold, but the conductive heat input to deep aquifers with local elevated permeability producing conditions suitable for a productive HSA that can be targeted by exploration. In an HSA play, there is a balance required in locating sufficient temperatures and permeability; temperature will increase with depth in a conductive temperature regime, however an increasing overburden with depth will also decrease the permeability of aquifer-hosting rocks. In the Midyan Basin, from oil and gas well temperature data, the geothermal gradient has been shown to be between 32-35 °C/km. To reach >100 °C it would be necessary to drill at least 3 km into the subsurface.

The exploration approach followed a typical greenfield exploration methodology. A desktop study was performed to assess the known information of the Midyan Basin from the standpoint of scientific literature and public data. This supported field visits directed at observing outcrops and verifying previously reported faulting.

The basin geometry was interpreted using potential field methods with the first interpretation based on the regional magnetics and gravity data from SGS Saudi Arabia, with supporting input from Tubbs et al. (2014). From the regional magnetic map below, there can be observed two magnetic lows, one in the south of the Midyan Basin close to the coast, and another low present in the back-basin, close to Al-Bada.

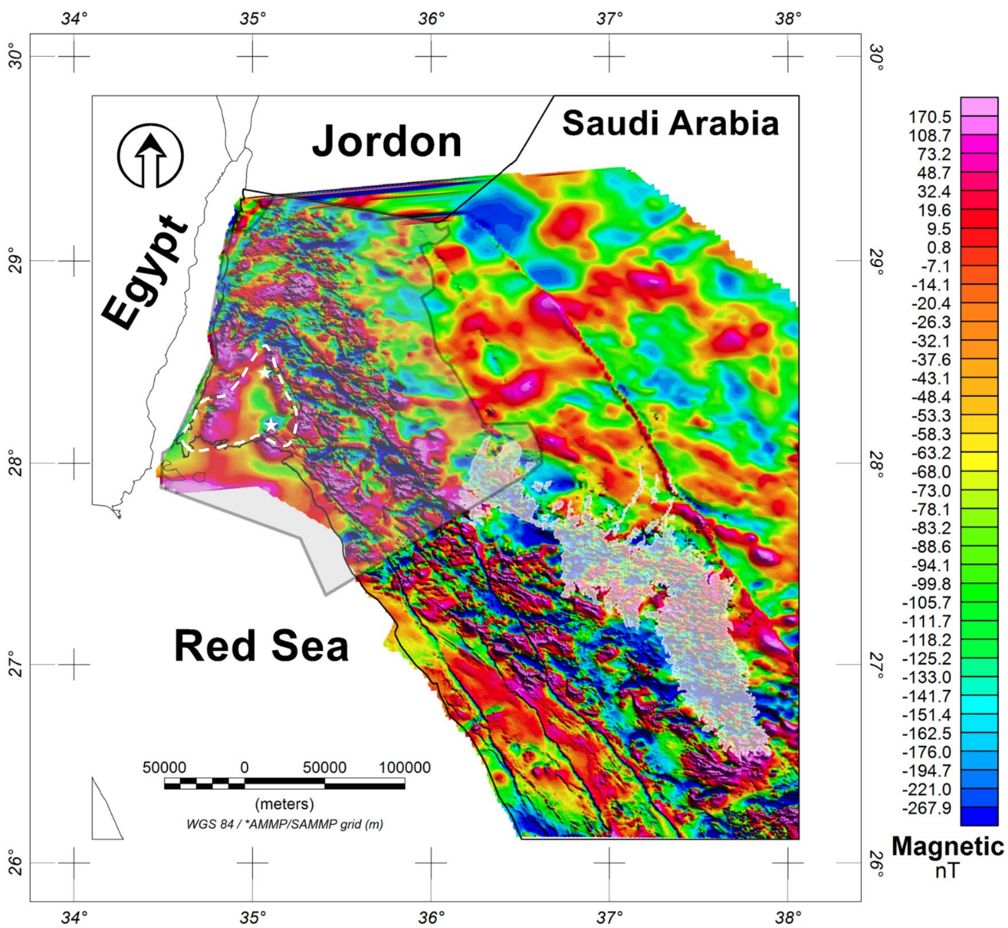

Figure 9. Regional magnetic map of Saudi Arabia. The NEOM area is outlined by the translucent polygon, while the Midyan Basin is outlined by the white dashed-line.

The observed magnetic lows were found to correspond to an interpreted low in the seismic lines presented by Tubbs et al. (2014). Comparing the seismic section in Figure 9 from Tubbs et al. (2014) to the magnetic anomaly map in Figure 10 , the location of the northernmost magnetic low in the Midyan Basin (shown as the northernmost white star in Figure 9) coincides with the deeper basement depicted in the seismic section northward towards A'. Similarly, the basement also seems to be dipping southwest towards the coast as shown in the seismic section in Figure 10. This also corresponds with a magnetic low in the south, as seen in Figure 9.

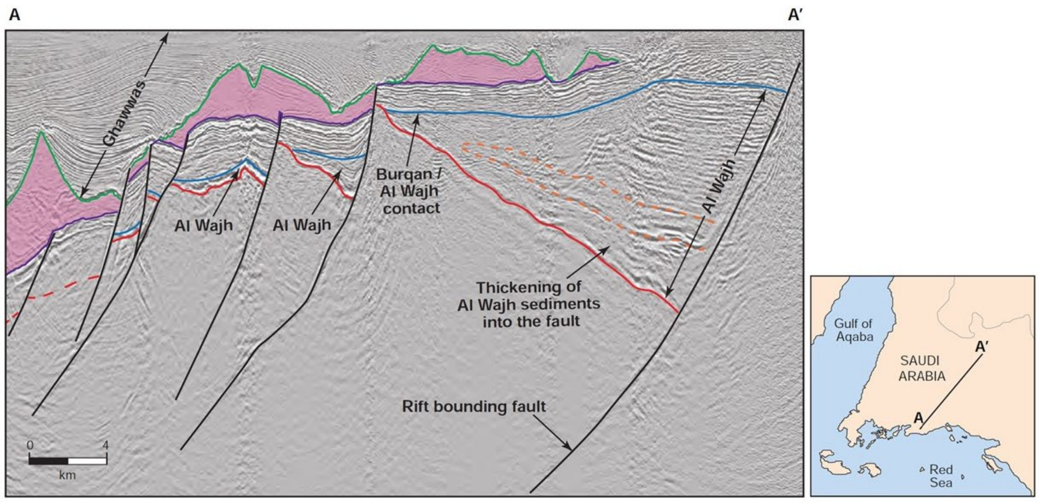

Figure 10. Interpreted pre-stack depth-migrated 3-D seismic section from Tubbs et al. (2014). Black lines = faults; green = top Mansiyah Formation; purple = top Maqna Group; cyan = top Al Wajh Formation, red = top basement. Highlighted in pink is the Mansiyah Formation. In this interpretation, the basement is deepening towards the northeast, towards A'.

The implied basin geometry derived from published regional magnetics and gravity along with the published seismic profiles from Tubbs et al. (2014) helped guide the location of seismic lines for a present day 2D seismic study which was performed to confirm the findings and further interpretation from already existing scientific literature. The resulting seismic profiles were used to map and confirm the depths to the granitic basement, map basin bounding faults and to define the sedimentary packages of the basin. Overall, the ideal geothermal targets in the Midyan Basin were determined to be found where the depth of the basement was the deepest, in that both a temperature of >100 °C and where permeable formations could be accessed. Numerous lithological units in the basin would make ideal reservoir targets, namely the Ghawwas, Maqna, Burqan and Al Wajh Formations. It will be required for any of these formations to be >3 km deep in order meet the target subsurface temperature of ≥100 °C.

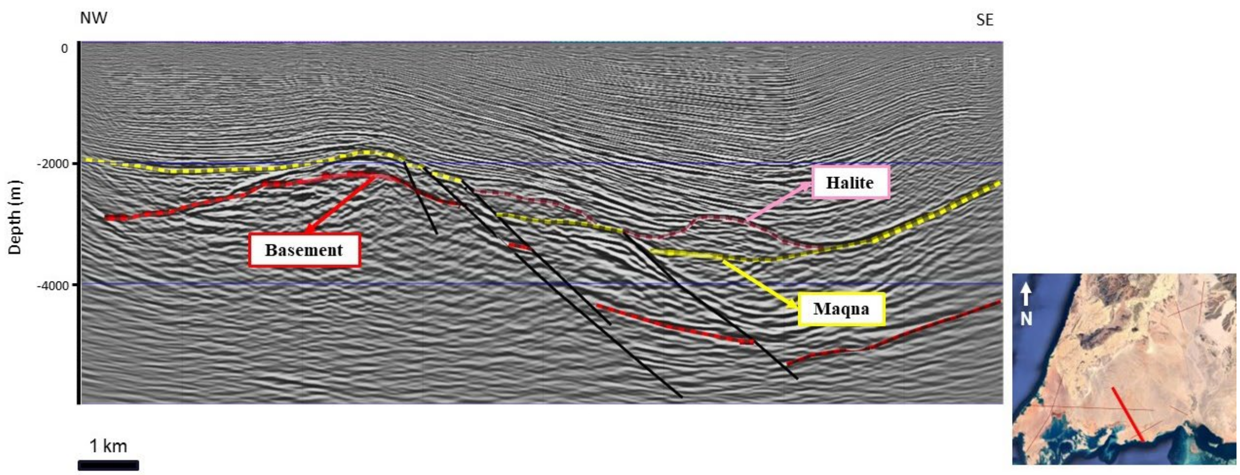

Figure 11 Newly acquired seismic showing the depth to basement exceeding 4 km on depth converted seismic sections. This makes the area attractive for geothermal development.

Based on the legacy data interpretation, the new seismic lines were acquired. Once processed, the 2D seismic sections revealed basin boundaries and depths. Detailed interpretations of the 2D data were performed and integrated with existing geologic information. Interpretation of the formation picks were divided into Basement, Pre-Salt (Maqna, Burqan and Al Wajh Formations), Salt (Mansiyah Halite), and Post-Salt segments (Ghawwas Formation). On the newly interpreted seismic lines, four (4) potential geothermal well locations were proposed in the Midyan Basin; three of the locations are closer to the coast in the northwest of Saudi Arabia, while the other is located more inland, farther north in the basin. It is in these locations where magnetic lows are encountered and where the basement is interpreted to be the deepest in the basin, thus increasing the likelihood of attaining both commercially viable temperature and permeability for geothermal utilization. These locations were either the center of the pull-apart basin from strike-slip displacement or the deepest points in the graben next to the basin bounding fault.

5. Conclusion

This study has demonstrated the potential of the Midyan Basin in the northwest of Saudi Arabia to host hot sedimentary aquifer (HSA) geothermal systems. Through a comprehensive exploration approach that included the analysis of regional geology, legacy well data, and newly acquired 2D seismic lines, several promising geothermal targets have been identified. These targets are located within deep syn-rift sedimentary reservoir-seal pairs that are deeper than 3 km and are predominantly found in marine turbidite sands or early-rift continental sands capped by marine shales.

The exploration work revealed that the Red Sea basin's tectonic history, characterized by stages of rifting and fault propagation, has significantly influenced the current structural configuration and sediment deposition. The depth to basement, a critical factor for geothermal exploration, was mapped using regional geophysics and seismic data. The deepest parts of the basin, where temperatures exceed 100 °C, were identified as the most viable for geothermal exploitation. These areas correspond to magnetic lows observed in regional magnetic maps and seismic profiles, indicating significant sediment thickness and optimal conditions for geothermal reservoirs.

The Midyan Basin's geological setting, with its complex interplay of rift and strike-slip tectonics, provides a unique opportunity for geothermal development. The identification of key lithological units such as the Ghawwas, Maqna, Burqan, and Al Wajh formations as potential reservoirs further underscores the basin's suitability for geothermal projects. The successful exploration and eventual development of these geothermal resources can contribute significantly to NEOM's vision of becoming a leading renewable energy hub, providing sustainable power, heating, and cooling solutions.

In summary, the exploration efforts in the Midyan Basin have laid a strong foundation for future geothermal development. The current study highlights the potential of the Midyan Basin to support large-scale geothermal energy projects, aligning with Saudi Arabia's Vision 2030 and the ambitious goals of the NEOM project. Future work should focus on detailed reservoir characterization, drilling exploratory wells, and conducting feasibility studies to further de-risk the identified geothermal prospects and pave the way for commercial geothermal exploitation in the region.

Acknowledgement

We would like to thank ENOWA-NEOM for their sponsorship of this work and approval to publish this paper.

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