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Preliminary Evaluation of Geothermal Potential in the Midyan Basin: Insights into the Hot Sedimentary Aquifer System of Northwestern Saudi Arabia

Vicky Rai Chandra[1], Triwening Larasati[12], M. Ghassan Jazmi Shalihin[1], Astri Indra Mustika[1], Ferdino R Fadhillah[2], and Serina Andiani Pongtuluran[1]

[1]PT. Geoenergi Solusi Indonesia, Cibis Nine 11th Floor, Jakarta Selatan 12560, Indonesia

[2]Geology Study Program, FMIPA, Universitas Indonesia, Depok 16424, Indonesia

vrc@geoenergis.com; vickyraychandra@gmail.com

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ABSTRACT

This study investigates the geothermal energy potential of the Midyan Basin in Saudi Arabia. Extensive geoscientific surveys conducted for geothermal, mining, and oil and gas exploration have revealed a significant heat gradient anomaly in the region. Data from deep oil and gas wells indicate temperatures reaching 115°C at a depth of 2,800 meters, with geothermal gradients of approximately 33–35°C/km, notably higher than the average intra-continental gradient of 25°C/km. Local geological factors, such as heat-conductive salt layers, granite intrusions enriched with radioactive minerals, and a permeable extension-strike-slip fault framework, likely enhance the gradient in specific areas.

The Midyan Basin's elevated heat anomalies are concentrated in the basin depocenter, primarily within the pre-salt formation reservoir. These reservoirs are highly fractured due to Red Sea rifting and activity along the Gulf of Aqaba strike-slip fault. The heat source is attributed to deep mantle processes and radiogenic heat from the granite basement. The salt formations act as cap rocks, trapping hot water within the pre-salt reservoirs. Potential reservoirs include the Al Wajh, Burqan, or Magna formations, sealed by the Mansiyah salt formation and interbedded silt, mud, and claystone layers.

1. INTRODUCTION

Geothermal resource provinces in Saudi Arabia are primarily located along the western coast and are closely associated with the Red Sea. These geothermal resources are most notable in volcanic fields, known as Harrats, and are evidenced by the presence of hot springs, particularly in Jizan and Al Lith. However, there are other potential areas, including the Midyan Basin in the northwest, which may host hot sedimentary aquifer systems along the western coast's basins. In the Midyan area, no surface thermal manifestations have been identified. Despite this, various studies, such as Aboud et al. (2023) and Alhani (2024), have reported high heat flow in the region and the existence of geothermal system, thus Chandra (2024) proposes the preliminary conceptual model. The absence of surface indicators could stem from several factors: the absence of hydrothermal activity, or the confinement of heat within a sedimentary basin forming a confined aquifer.

This paper presents findings from surface geoscientific investigations conducted in the Midyan area, shedding light on its geothermal characteristics. We examine geological and geophysical data, evaluate the potential for a hot sedimentary aquifer system, and propose recommendations for further geothermal exploration and development. Understanding the geothermal potential of the Midyan Basin can support Saudi Arabia’s efforts to diversify its energy resources and advance global initiatives for sustainable energy solutions.

2. REGIONAL SETTING

The Midyan Basin is shaped by the geological processes of the Red Sea rifting and the strike-slip movement along the Gulf of Aqaba. The Red Sea rifting is part of the Afar triple junction, where the Arabian, Nubian, and Somali Plates diverge, forming the Red Sea Rift, Gulf of Aden Rift, and Main Ethiopian Rift. Extending from the Afar region in the south to the Gulf of Suez in the north, the Red Sea Rift initially included the Gulf of Suez, which shares its geological history and structural characteristics. The Red Sea Basin contains multiple half-graben zones, dipping towards either the Arabian or African Plates, separated by accommodation zones (Figure 1). These structural features are well-documented in the Gulf of Suez and are observed throughout the Red Sea region.

The Gulf of Aqaba opened during the Late Oligocene to Early Miocene (~15 Ma) through extensional rifting initiated at the Afar triple junction. By the Early to Middle Miocene (~10 Ma), left-lateral strike-slip motion along the Dead Sea Transform formed pull-apart basins and en echelon faults. Since the Late Miocene (~5 Ma), ongoing strike-slip faulting and seismic activity have shaped its deep linear basins, linking the Red Sea Rift to the Dead Sea Transform (Tubbs, et al., 2014).

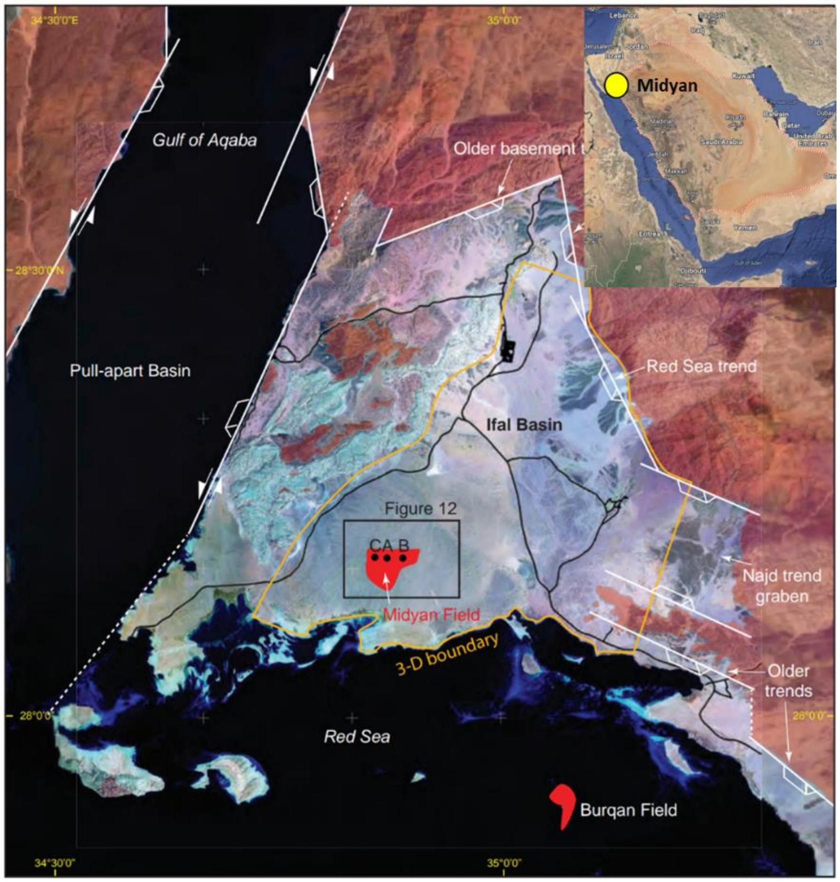

Figure 1: Tectonic framework of the Midyan Area (modified from Tubbs, et al., 2014).

2.1 The Red Sea Rift Development

The Red Sea Rift began 30–32 million years ago due to the subsidence of the Afar plume, fracturing the African-Arabian continental plate and gradually evolving into an oceanic rift. Before the onset of the rifting period, pre-Miocene formations, including the oldest Cretaceous formations, were present. These formations are thickest in the Gulf of Suez and gradually thin out towards the south, becoming absent offshore and in outcrops in the northern Red Sea region. However, some Cretaceous outcrops are preserved within grabens along Saudi Arabia's western coast, extending to the Yemen border.

a. **Early Rift Stage (31-27 Ma)**
   During the early rift stage, characterized by normal extension, the entire 2,200 km long Red Sea opened simultaneously. At this time, the Early Oligocene deposits consisted of continental sands from the Al Wajh formation, present as continental red beds and lacustrine deposits up to 2200 meters thick. This period was followed by a marine incursion that deposited deep marine turbidites of the Burqan formation in tectonically active regions (Bosworth, Huchon, & McClay, 2005).
b. **Mid-Rift Stage**
   During 18-17.5 Ma, a significant environmental change occurred, marked by mid-clysmic unconformity during the Burqan sedimentary deposition. This event ended the deposition of the Maqna group, which showed low tectonic activity and basin-wide restriction, leading to the formation of regional anhydrite layers and the extensive Mansiyah halite (Bosworth, Huchon, & McClay, 2005).
c. **Late Rift Stage (14-12 Ma)**
   The Gulf of Aden rift evolved into an oceanic ridge with seafloor spreading. The collision between the Arabian and Eurasian plates rotated the Arabian plate counterclockwise, shifting the Red Sea to a rift-oblique extension. This reactivated faults and caused strike-slip deformation, particularly in the northern Red Sea and the Midyan peninsula (Bosworth, Huchon, & McClay, 2005).

2.2 The Gulf of Aqaba Opening

The counterclockwise rotation of the Arabian plate causes the opening of the Gulf of Aqaba, halting extension along the Gulf of Suez. This created strike-slip deformation across the basin, along the Gulf of Aqaba, and extended to the Dead Sea at the further north. This is also altering subsalt topography and causing the Mansiyah halite to move towards the center of the Red Sea. This process formed accommodation zones filled by the post-salt Ghawwas and Lisan formations.

a. Phase 1 (`15 Ma): Initial Phase – Onset of Rifting and Early Extensional Tectonics

The opening of the Gulf of Aqaba began during the Late Oligocene to Early Miocene as part of the larger tectonic activity at the Afar triple junction, where the Arabian, African, and Somali Plates diverged. Mantle upwelling initiated rifting along the Red Sea, propagating northward and creating extensional forces that affected the northern part of the Arabian Plate. This extensional tectonism resulted in lithospheric thinning and the formation of grabens and half-grabens, laying the groundwork for the Gulf of Aqaba. Pre-existing lithologies, including Neoproterozoic basement rocks and syn-rift sediments, influenced the structural configuration of the region (Tubbs, et al., 2014).

b. Phase 2 (~10Ma): Mid Phase – Strike-Slip Faulting and Pull-Apart Basin Development

During the Early to Middle Miocene, as the Arabian Plate moved northward relative to the African Plate, the tectonic regime shifted from extension to left-lateral strike-slip motion along the developing Dead Sea Transform Fault system. This change marked the transition from rift-dominated to transform-dominated tectonics. The Gulf of Aqaba experienced significant faulting, resulting in the development of pull-apart basins and en echelon fault systems. These basins formed due to localized extensional forces within the broader strike-slip regime, allowing significant sediment accumulation. Evidence from seismic surveys and sedimentological data confirms the formation of these pull-apart structures, which are integral to the Gulf's geological evolution (Tubbs, et al., 2014).

c. Phase 3 (`5Ma): Late Phase – Structural Maturity and Ongoing Tectonic Activity

The Gulf of Aqaba reached its current configuration during the Late Miocene to Recent, as strike-slip motion along the Dead Sea Transform became the dominant tectonic force. The region is now characterized by deep basins bounded by steep normal and strike-slip faults. Ongoing left-lateral motion along the transform fault, coupled with seismic activity, highlights the dynamic nature of the region. Active faulting and sedimentary processes have further modified the basin's structure. Studies show that modern seismicity is concentrated along major fault systems, confirming the Gulf's role as a tectonically active zone linking the Red Sea Rift to the Dead Sea Transform (Tubbs, et al., 2014).

3. GEOLOGY OF MIDYAN

The geological model of the Midyan Basin has been largely developed using 3D seismic data from hydrocarbon exploration (Tubbs, et al., 2014) and recently acquired 2D seismic data for geothermal exploration (Alhani, et al., 2024). The seismic line location is depicted in Figure 2 with some profile presented in Figure 3. The model is further supported by regional magnetic data and surface fault mapping. The Midyan Basin is predominantly characterized as a half-graben structure (Figure 3), formed by extensional tectonics during the Miocene. Its structural framework consists of a series of normal faults that play a key role in the deposition and preservation of sedimentary layers. Additionally, the basin is influenced by the strike-slip movements of the Gulf of Aqaba and the Dead Sea Fault, as evidenced by strike-slip faults visible in surface rock scarps and pull-apart structures within the region.

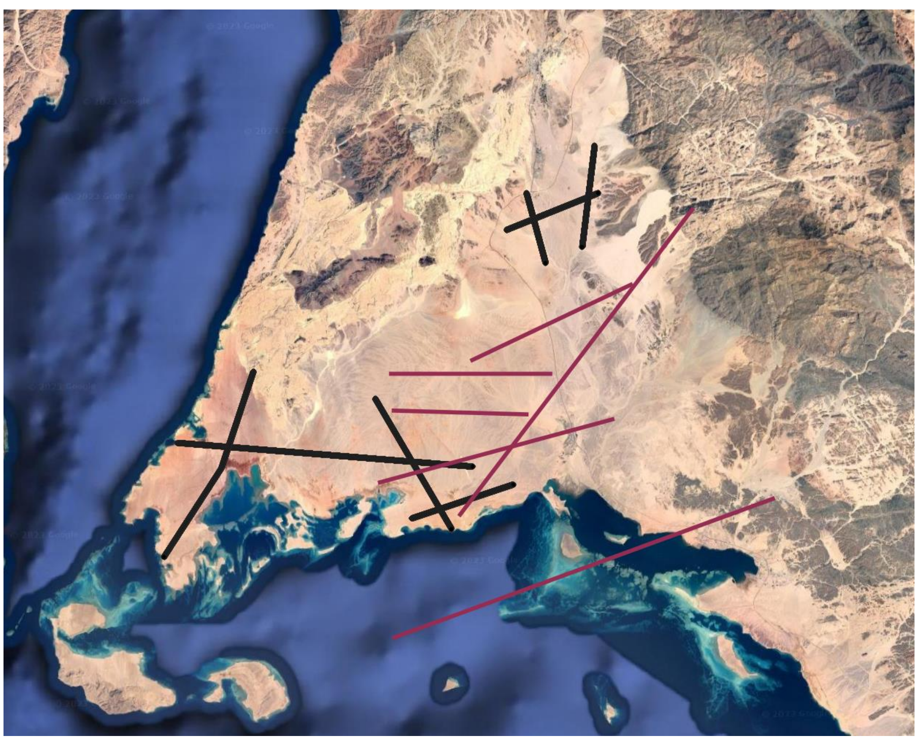

Figure 2: The seismic line across the Midyan area. The Red line is from Tubbs, et al. (2014) and the Black line is from Alhani, et al. (2024).

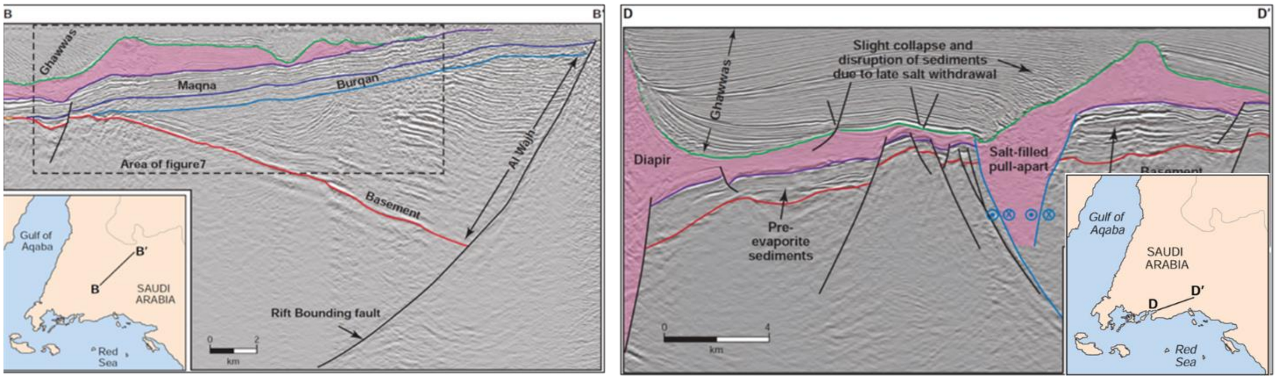

Figure 3: Seismic profile of Midyan basin (modified from Tubbs, et al., 2014).

The basin fill consists of thick sequences of syn-rift siliciclastic rocks, deposited primarily during periods of tectonic activity. The pre-rift section includes a Neoproterozoic basement, predominantly granitic, along with metasediments, metavolcanics, and gabbro, as well as localized deposits of Cretaceous Adaffa Sandstones (Clark, 1987 in Tubbs et al., 2014). The syn-rift section comprises the Al Wajh Formation, Burqan Formation, Maqna Group, and Mansiyah Formation, while the post-rift section includes the Lisan Group, Ghawwas Formation, and post-Ghawwas Formation (Hughes & Beydoun, 1992; Beydoun, 1991). Further explanation of each formation/group is explained below, also illustrated in a simplified manner in Figure 4. The generalized stratigraphy is illustrated in Figure 5.

a. **Ghawwas Formation (post-salt)**: A post-salt formation heavily influenced by salt evacuation, which controls its accommodation space and structural characteristics. The dynamics of salt movement have significantly shaped this formation and its associated geological features.
b. **Mansiyah Formation (salt)**: Characterized by massive halite deposits, this formation reflects the peak of basin-wide restriction and reduced subsidence. It marks the end of the active rift phase along the Red Sea faults and the Gulf of Aqaba strike-slip zone. The Mansiyah salt acts as a regional seal, effectively capping the Maqna Group unless offset by faults exceeding the remaining salt thickness.
c. **Maqna Group (pre salt)**: During its formation, rift activity began to slow onshore, leading to basin-wide restrictions. This group includes siliciclastic/carbonate layers and anhydrite beds, which form vertically stacked reservoir-seal pairs, with the anhydrite layers serving as effective seals.
d. **Burqan Formation (pre salt)**: Marking the first basin-wide marine incursion, this formation signifies the onset of organized rift propagation across the Red Sea basin and its connection to global oceans. It is composed of marine turbidites with interbedded sandstones and mudstones/shales, creating vertically stacked reservoir-seal pairs.
e. **Al Wajh Formation (pre salt)**: This represents the earliest rift-related deposition, consisting of continental red beds that form sand wedges over the basement, primarily within rotated half-grabens. It likely features high-porosity sandstone interspersed with tighter facies in shales deposited in lacustrine settings.

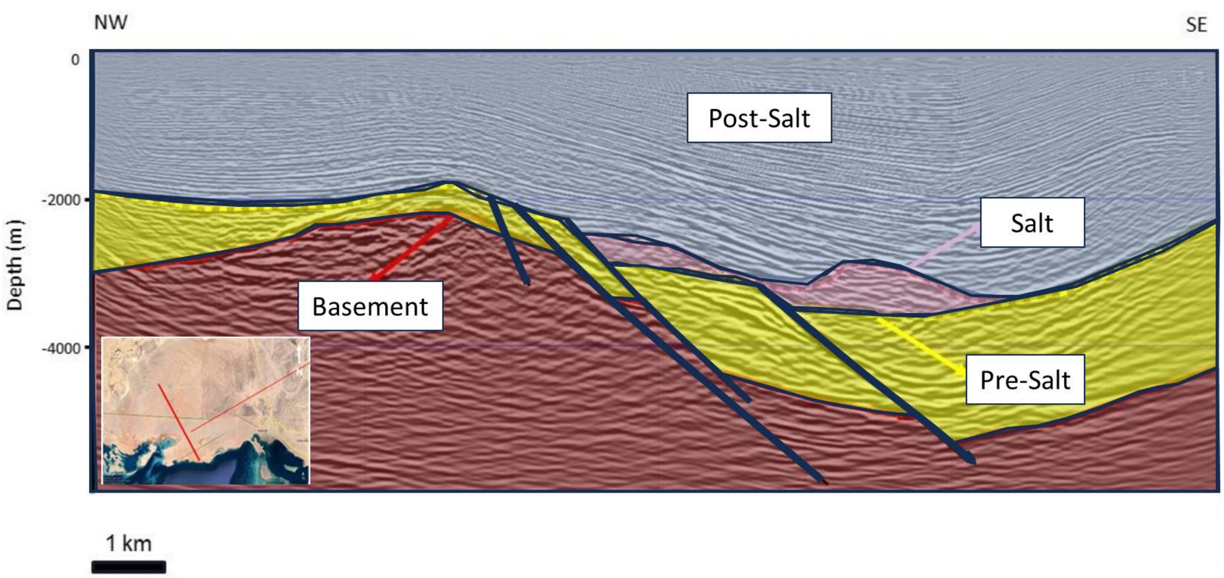

Figure 4: Simplified stratigraphy stack of Midyan basin (modified from Alhani, et al., 2024).

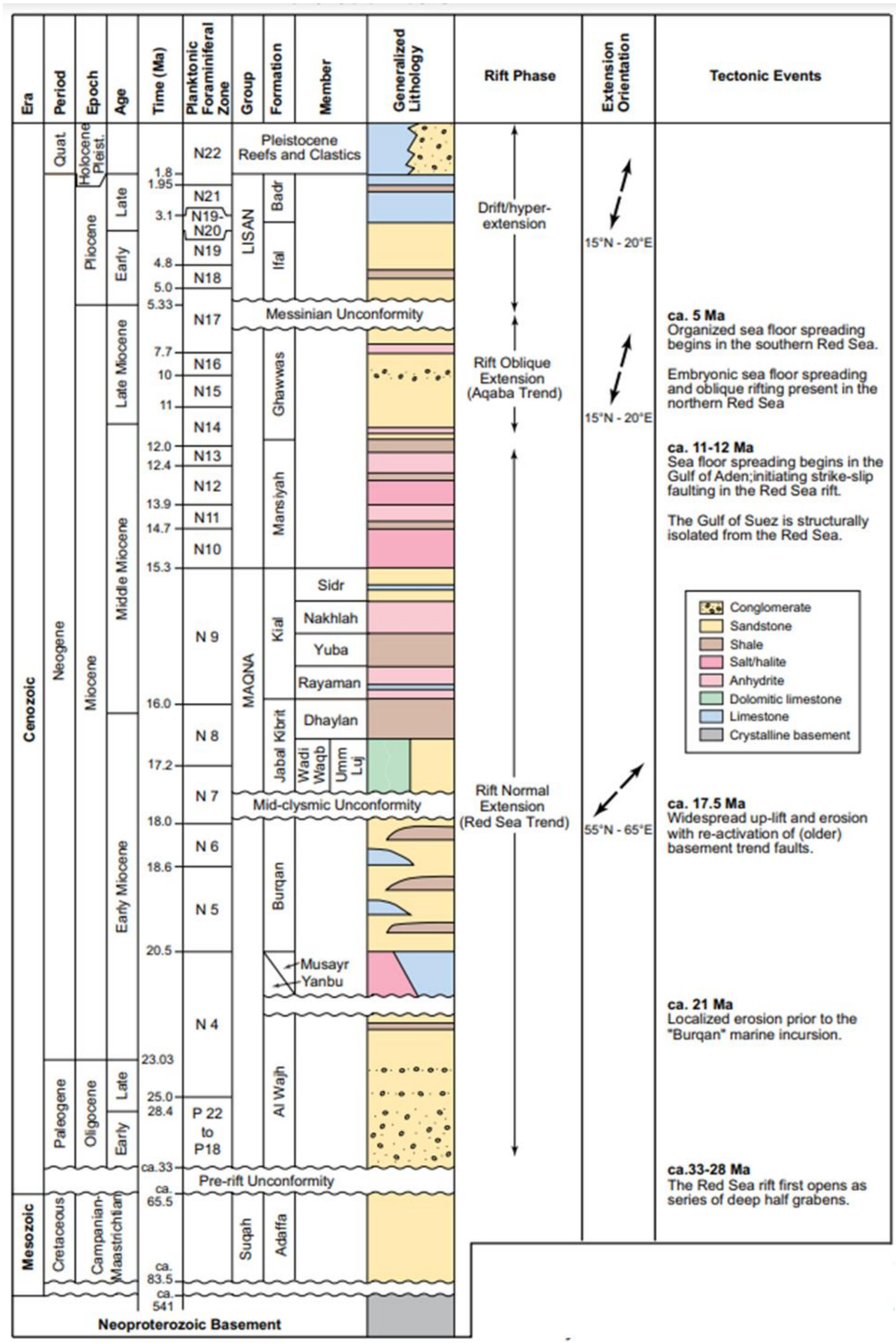

Figure 5: Generalized stratigraphy of Midyan Peninsula (Tubbs, et al., 2014).

4. GEOTHERMAL SYSTEM PARAMETER

Currently, no geothermal drilling explorations have been conducted in the Midyan area to validate the subsurface parameters used in constructing the geothermal conceptual model. The model has so far relied on surface geoscience data supplemented by oil and gas well information. Comprehensive geoscience surveys, including 2D and 3D seismic surveys, have been carried out, while regional magnetic data has identified basement anomalies and estimated the Curie depth. Gravity data from the Saudi Geological Survey has further refined interpretations of basement distribution and inferred faults. Surface geological mapping has documented lithologies, faults, and fractures, but the absence of surface geothermal manifestations presents interpretational challenges.

The geothermal system in Midyan is classified as a hot sedimentary aquifer type. Key resource parameters include temperature, permeability, reservoirs, and cap rocks. The primary heat source likely stems from deep crustal thinning, with radiogenic decay in the granite basement contributing to the heat anomaly. Heat is conducted through the basement, and ascends via faults and fractures, with convective heat transfer occurring in sedimentary layers.

4.1 Subsurface Temperature

There is limited subsurface data available in this area, sourced only from several deep wells (Figure 6 and Figure 7). The quality of this data is uncertain, as the actual conditions of the wells are unknown. Additionally, the details regarding the measurement procedures, tool specifications, and the times at which measurements were taken are absent, making it impossible to conduct a data quality check. From the deep wells, it is observed that the maximum temperature can reach 110°C at a depth of 2600 m, suggesting a temperature gradient of about 33-35°C/km for the deep formation.

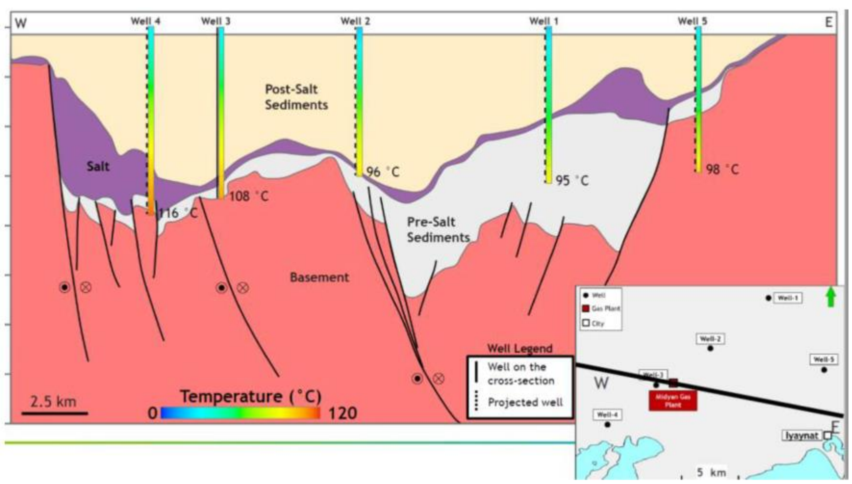

Figure 6: Simplified geological cross section showing the location of several hydrocarbon wells with the measured temperature (Alhani, et al., 2024).

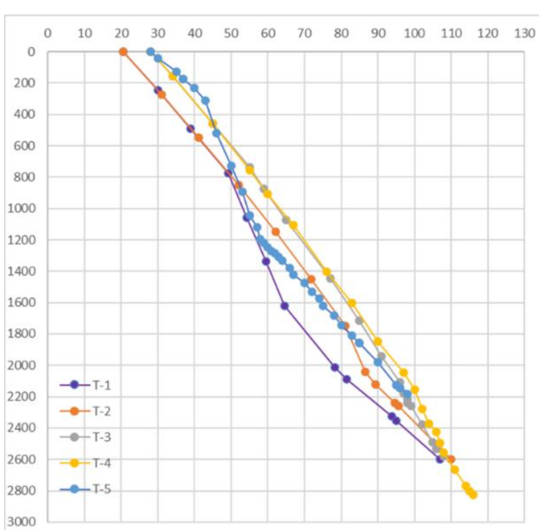

Figure 7: Temperature data from hydrocarbon exploration wells (Alhani, et al., 2024; Chandra, et al., 2024).

4.2 Reservoir Formation

The hot water reservoir in the Midyan area is influenced by the distribution of stratigraphic layers, with water stored in porous sedimentary rocks and at sharp formation contacts. The presence of alternating permeable and impermeable strata results in predominantly lateral water movement within the formations. The most promising reservoirs are pre-salt formations, including the Al Wajh, Burqan, and Magna formations, as well as their formation contacts. The bottom of the Ghawwas formation (post-salt) also holds reservoir potential, though its temperatures may be lower.

Structural features of the Midyan basin, such as rift-bounding faults formed by Red Sea spreading and pull-apart fault systems from Dead Sea strike-slip motion, significantly impact the reservoir's geothermal potential. Heat from the thinning crust is transported upward by conduction through basement rocks and convection along faults, with reservoirs near these faults likely experiencing higher temperatures. However, these faults may not host significant water volumes. Permeable basement contacts, characterized by sharp unconformities, also serve as important conduits for heat and water, aided by radiogenic heat from the basement.

Key reservoir and permeability targets for this hot sedimentary aquifer system include:

a. **Top Basement Unconformity**: The top basement in the Red Sea, often heavily fractured and overlain by continental sands of the Al Wajh formation, offers significant reservoir potential.
b. **Al Wajh Sands**: These sands, capped by an intra-Al Wajh facies seal or the Burqan formation seal, are another viable target.
c. **Burqan Formation Sandstones**: These sandstones, capped by inter-formation seals, present promising reservoir prospects.
d. **Maqna Group Reservoirs**: Capped by the anhydrites within the group or the Mansiyah salt, these reservoirs are attractive geothermal targets.
e. **Bottom of Ghawwas Formation**: Located at the contact with the Mansiyah salt, this formation benefits from the salt's good thermal conductivity, efficiently transferring heat from below to above the salt layer. This allows access to the thermal properties without intersecting the salt layer, which is known to complicate drilling operations.
f. **Major Rift-Bounding and Pull-Apart Faults**: These faults play a crucial role in heat distribution and can enhance the geothermal potential of adjacent reservoirs.

Understanding the interplay of stratigraphic and structural features allows for more effective targeting of geothermal reservoirs, optimizing exploration efforts in the Midyan area.

4.3 Cap Rock

The presence of geothermal clay cap is unlikely in the Midyan area. Instead, the impermeable rocks within the formation and the salt layer originally deposited, are more likely to cap the reservoir. The intra-layer clays identified in several formation, such as:

a. The red and green mudstones in the Al Wajh formation (Hughes & Johnson, 2005) potentially act as caps for the porous sandstones below.
b. The calcareous mudstone of the Subayti member and the mud-dominated succession of the Nutaysh member of the Burqan formation (Hughes & Johnson, 2005).
c. The deep marine mudstone of the Magna formation (Hughes & Johnson, 2005).

The presence of salt formations in the Midyan area can be identified through seismic line profiles in Tubbs, et al. (2014) and Alhani, et al. (2024). Similar to the impermeable clay, the salt layer caps the reservoir underneath, however the high thermal conductivity of the salt body allows the heat escape from the reservoir. Apparently, the distribution of the salt layer would control the heat flow direction, see a study by Zui, Dubanevich, & Vasilionak (2016) that concludes the heat flow direction controlled by salt layer in the Pripyat field, Belarus.

Due to their high thermal conductivity, salt layers can act as efficient channels for heat, creating local positive thermal anomalies in the overburden of salt accumulations (Moeck & Breadsmore, 2014; Moeck, 2014). This unique property makes the areas above these formations are attractive targets for geothermal exploration, as the heat is channeled through the salt, creating a distinct temperature change in salt topography. Daniilidis & Herber (2017) demonstrated a 40% increase in energy extraction and a 25°C temperature rise within a salt formation in the north of the Netherlands, emphasizing the influence of salt thickness variations on heat gradients and thermal conductivity scenarios. Additionally, the geometric shape of salt domes affects heat accumulation, with narrower domes leading to less concentrated heat compared to elongated, conical structures (Daniilidis & Herber, 2017).

4.4 Proposed Conceptual Model

The elevated heat recorded in well temperature data from the Midyan area reflects a thermal gradient of 35°C/km, primarily due to crustal thinning associated with Red Sea spreading. Magnetic data reveals a Curie Point Depth (CPD) of 12–15 km, aligning with an inferred thermal gradient of 33–35°C/km, consistent with well observations. This suggests that deeper porous rocks can retain hotter water. Radiogenic heat from the basin's high-radioactivity granite also contributes significantly to the system's thermal profile. Local variations in the thermal gradient arise from the presence of the salt layer, which influences heat flow direction. Accurate salt modeling is thus essential for optimizing exploration drilling and better understanding heat distribution (Chandra, et al., 2024).

Reservoir rocks identified from seismic profiles are primarily pre-salt formations, including the Al Wajh, Burqan, and Magna formations, consisting of sandstone stacks interbedded with claystone acting as impermeable barriers. These formations may host multiple reservoir zones within a single location, requiring unique production wells to accommodate this unconventional reservoir structure. Additionally, deep fractured zones enhance vertical permeability, complementing the lateral permeability within sedimentary rock layers.

The hydrology of the Midyan area remains poorly understood, despite the presence of numerous geotechnical boreholes. Limited data and the shallow depth of these boreholes hinder insights into deeper hydrological patterns. Closer to the shoreline, saltier water is encountered, but this does not necessarily reflect the characteristics of deeper reservoir water. The proposed conceptual model is illustrated in Figure 8.

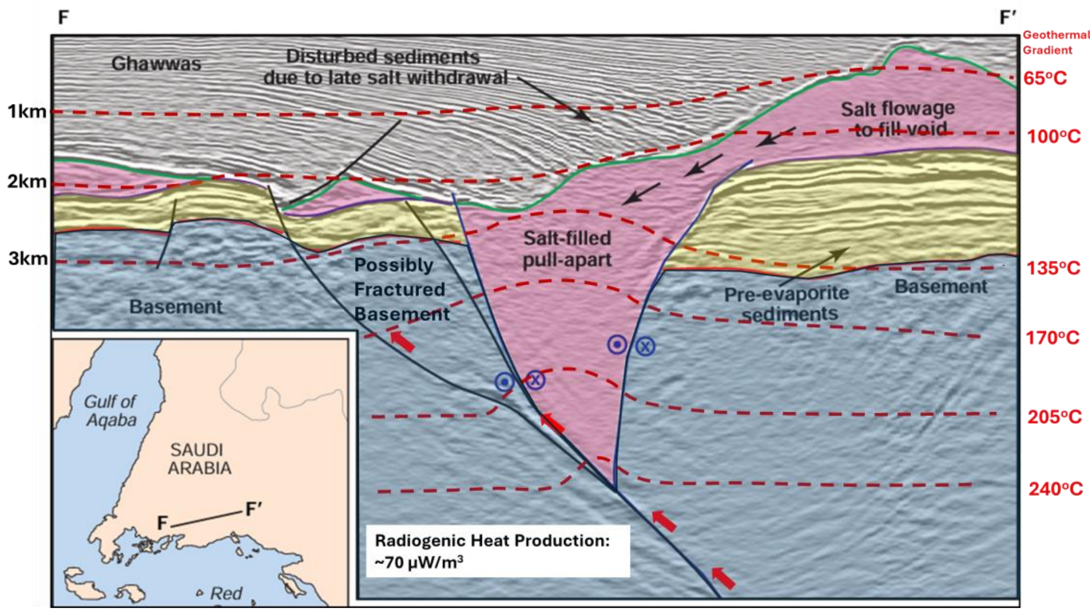

Figure 8: Proposed resource conceptual model in Midyan area (modified from Chandra, et al. 2024). The geothermal gradient is inferred from the curie depth; The radiogenic heat production is analog from the closest surface granite analysis; Basement rocks are in dark gray, potential reservoir rocks in yellow, and the massive impermeable salt layer in pink.

5. UNCERTAINTY AND RECOMMENDATION

The proposed conceptual model requires validation as it is based on limited data. While the geological framework of the area has been extensively documented through studies primarily focused on oil and gas exploration, the geothermal potential remains underexplored. To enhance exploration efforts, a comprehensive strategy is recommended, including detailed structural mapping, high-resolution 3D seismic surveys, advanced magnetic surveys (airborne or ground), precision gravity surveys, and ultimately exploratory drilling.

Key uncertainties in the conceptual model include:

a. **Heat source**: Temperature profiles from multiple wells in the area are not fully understood, complicating the interpretation of thermal data. The inferred Curie depth from regional magnetic data (Aboud, et al., 2023) reflects the depth of the demagnetized mantle zone rather than actual isotherm contours. Additionally, radiogenic heat production estimates from surface granite samples may not accurately represent the Neoproterozoic granite of the Midyan basement, which could have reduced radioactive mineral content over time.
b. **Salt layer**: The Mansiyah salt layer, identified through 3D seismic profiles, requires lithological sampling to confirm its mineral composition and measure its thermal conductivity. Comprehensive 3D modeling of the salt body is crucial for refining the geological and geothermal framework.
c. **Cap rocks**: Potential cap rocks (e.g., siltstone, mudstone, and claystone) cannot be definitively identified using current 3D seismic profiles, which lack the resolution to differentiate between sand and clay formations. Analog data from oil and gas exploration in the Suez and Sinai Peninsula are insufficient, and direct exploration drilling is needed to verify the presence of smear clay along faults.
d. **Reservoirs**: Pre-salt reservoirs, interpreted based solely on 3D seismic data, include formations such as Al Wajh, Burqan, and Magna. Each has distinct lithological properties, pressure regimes, and permeability that could significantly affect reservoir characteristics.

Advanced geoscientific techniques can address some uncertainties, but deep geothermal drilling is indispensable for substantial improvement. As the Midyan area is identified as a hot sedimentary geothermal system without surface manifestations, resolving all uncertainties without drilling is unlikely. Transitioning to deep exploration drilling is strongly recommended to refine the conceptual model and unlock the area’s geothermal potential

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