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**Research Paper**

# 2D Model Subsurface of the Red Sea Based On Gravity Satellite Data

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***ABSTRACT***
*The Red Sea is one of area on the earth where the tectonic plate undergo rifting which has extensional feature. As an effort to study the subsurface of Red Sea can be done by create and interpret the subsurface condition with two dimensional gravity profile. This study aims to determine the gravity anomaly and subsurface conditions in the Red Sea and its surroundings as seen from gravity satellite data, and to interpret the tectonic model. This study uses free air anomaly data and topography from satellite data which is then processed and modeled with Oasis Montaj. The modelling carried out resulted in the gravity anomaly in the Red Sea and its surroundings having different closures, the Northeastern part of the study area showed the dominance of high closures marked with pink to orange colors, while the low-closure is marked in light blue to dark blue and the medium-closure is green to orange. The two-dimensional model proves that there is a relationship between the formation of the Red Sea and the geodynamic processes that occur. Red Sea tectonics based on gravity data shows prolonged stretching and spreading of the continental crust seen from asymmetrical and symmetrical stretching models. The formation of new oceanic crust occurs under the Red Sea, undergoing evolution which results from the process of stretching the continental crust. The timing and distribution of crust in the Red Sea was influenced by the forces that led to subduction due to complex plate interactions along the northern edge of the Arabian plate during the Early Miocene. Magmatism focused on the Arabian margin and the Afar plains which began to be active since the Miocene.*

***Keyword:*** *Gravity, bouguer anomaly, 2D model, the Red Sea, rifting zone*

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## I. INTRODUCTION

All processesthatoccurstartingfromcontinentaldivisionandplatedevelopment are explainedbyWilson'scycletheory. One ofthestages in the Wilson processistheprocessofcontinentalexpansion (rifting), namelytheprocessofcontinentalcrustexpanding, thinningtoformsedimentarybasinsormaficgroups. This can be seen in the formation of the Red Sea which entered the initial rifting phase of the Wilson cycle (Fitcher, 1999). The Red Sea is one of the areas on earth where tectonic plates are undergoing a process of expansion or separation. This area is characterized by the presence of extensional features (Bohannon, 1989), this attracted the attention of the writer so that it was used as a research target location.

The sedimentary basin thatformed in the Red Sea wasalsoformedduetocrustalthinning, sedimentaryandvolcanicloading, andcrustaldesificationprocesses. Nowadays, geologistsrealizethattheoriginsofthe Red Sea are relatedtocrustalmovementsandplatetectonicprocesses, sotounderstandthereconstructionoftheformationofthe Red Sea requires modeling fromsecondary data.

As aneffortto study theconditionoftheearth'ssubsurface, itcanbedonebycreatingandinterpretingtheconditionofthesubsurfaceusingtwo-dimensionalorthree-dimensionalprofilesbasedongravity data. The useofgravitysatelliteimage data is a developmentoftherelativegravitymethod. To obtainthedesiredgravityvalueusinggravitysatelliteimagery, thereisnoneedtomeasuregravityanomaly data in thefield, youonlyneedtoaccessthe TOPEX pagewhich has beenprovidedbytherelevantparty. Basedonthe modeling created, itwillproduceaninterpretationofthetwo-dimensionalshapeofthesubsurfacerocklayersthat are the target oftheresearch.

Theresearchaimsis toreconstruct a tectonic model basedon a subsurface model fromgravitysatellite data in the

Red Sea anditssurroundings.

## II. METHOD

The data used in thisresearchwasobtainedfromsatelliteimagerywhichcanbeaccessedonthewebsitehttp://topex.uscd.edu/cgi-bin/get_data.cgiprovided by*Script*InstitutionofOceanography, Universityof San Diego, USA. The data used in thetwo-dimensional modeling are elevation data andgravityanomaliescorrectedforfree air whichhavebeenarranged in a grid in ASCII-XYZ format, accordingtotheenteredboundaries. Becausetheanomaliesobtained are still in theformoffree air correctedanomaly data, furthercorrectionisneededtoproduceBougueranomalieswhich are readyfortwo-dimensional modeling. The softwareused in thisresearchis Microsoft Excel for data processing, and Oasis Montajfor making correctionsand modeling. The model resultsobtained were matchedwiththegeologicalconditionsoftheresearch area obtainedfromliteraturestudies.

## III. RESULTS AND DISCUSSION

***Topography of the Red Sea andSurroundings***

Most of the topographic features in the Red Sea are deep along the axis and high on several sides of the basin (**Figure 1**). The axial trough stretches from south of Ras Mohammed in southern Sinai to the Zubayr Islands, an area off the coast of Yemen. The main trough has a deep depth seen from the darker color. The Red Sea coastal plain was formed due to interactions between tectonic, sedimentary and biotic activity, this can be seen from the many structures and elevations with different slopes. There are no permanent rivers flowing into the Red Sea, as seen in **Figure 1**. The long, winding Barka River has no branches flowing into the Red Sea. The diversion of the Barka river is due to tectonic activity. The absence of rivers that empty into the Red Sea means that the supply of incoming sediment is small.

The southern portions of both sides of the Red Sea on the Arabian and African sides has paired curves and cuts indicating the beginning of rift geometry. The northern part of the Red Sea coastline does not have the same morphology as the southern part but appears parallel, which does not indicate the beginning of the rifting process but is the result of young bedrock and is influenced by faults (Bosworth and Burke, 2005). Inland coastal plains in areas with high elevation coastlines occur along the Red Sea. The plateau from Taif (Saudi Arabia) to Taizz (Yemen) along the border of the Arabian plains is bordered by steep erosional slopes with the highest peaks of 3 km (Coleman, 1993). Eastern Ethiopia has a steep cliff morphology with an elevation of around 2 km. The morphology of the Afar looks more complex with the presence of the Danakil horst near the coast and the Afar depression. Along the Sudanese plain, the elevation of the Red Sea is greater than 1 km, continuing north towards Egypt and the western part of the Gulf of Suez with bedrock of 1.4 – 2 km. The Afar experienced uplift during the early - late Oligocene, the beginning of this process was marked by the fission track cooling process (27-20 million years).

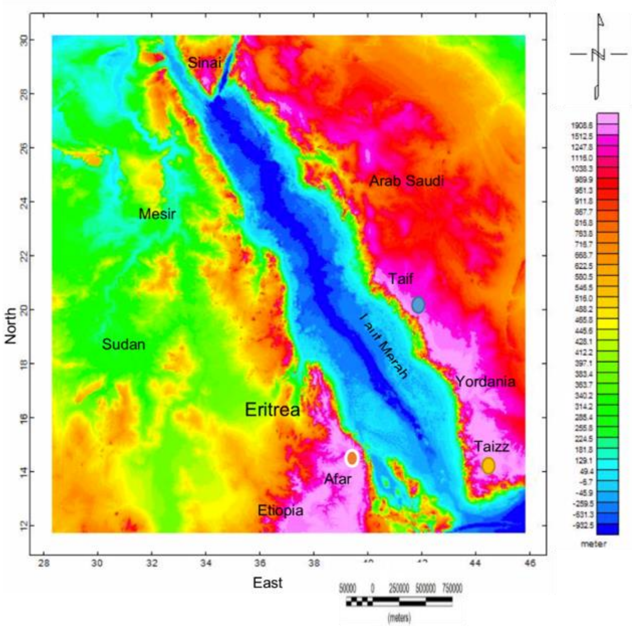



Figure 1. Topography map of Red Sea

***Bouguer Anomaly***

The gravity anomaly value for the research area obtained from Topex satellite data ranges from –28.8 – 78.8 mGal. To determine the distribution pattern of gravity anomalies, an interpolation process is carried out to form the gravity contour shown in **Figure 2**. The interpolation results show that there is a difference in low closure, medium and high. The northeastern part of the study area shows a dominance of high levels marked by pink to orange with a value range of 14 – 78.8 mGal. Medium chlorine with a yellow to light green color is more dominant in the southwest to northwest areas of the study area with a value range of -4.5 – 12 mGal. Low tides with a more dominant blue color extend from the northwest to the southeast of the study area, precisely along the Red Sea. It can be seen that areas with high anomaly values have low topography, while areas with low anomalies have high topography.

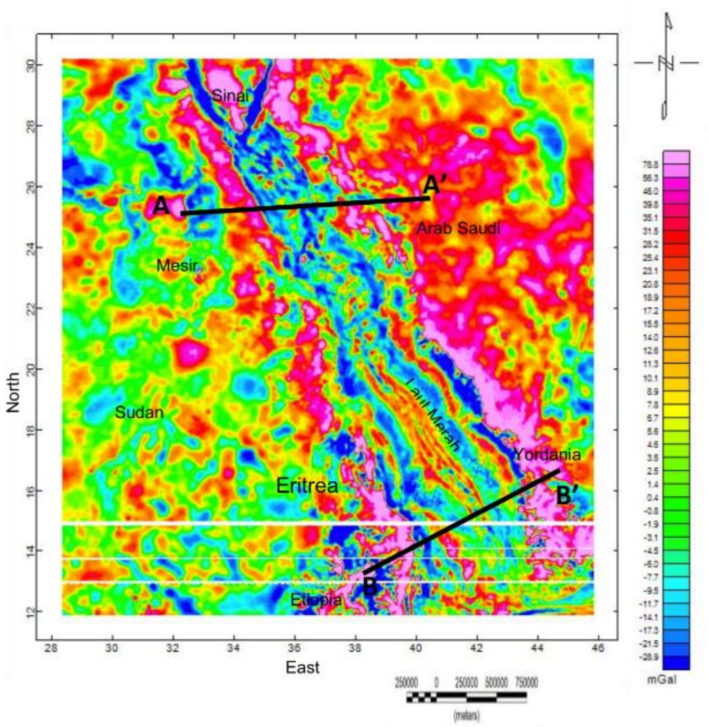



**Figure 2**. Bouguer anomaly map

***2D Modeling Inversion***

The main feature that can be seen from the gravity data for the study area is the large difference between the positive and negative gradients of the Bouguer anomaly in the east in the form of Precambrian rocks and negative values (close to 0 mGal) along the Red Sea (**Figure 2**). The low value of the gravity anomaly is influenced by the thick accumulation of Miocene evaporite deposits (Gettings, 1977). The discontinuity extends from northwest to southeast where the gravity value has a high value on the inner side of the coastal plain which causes the exposure of gabbro and mafic dike layers. The difference in the steep gravity gradient from the coastal plain to the large negative values in the Precambrian shield is indicated as the boundary of oceanic crust and continental crust (Gettings, 1977).

The line of the A-A' profile due to the gravity gradient between the Red Sea and the Arabian Shield is related to rifting of the continental crust at the edge of the rift margin. As a basis for quantitative interpretation of subsurfaceconditions, the rock mass classification by Telford (1990) is used, so that it can provide information about the subsurface lithology around the Red Sea. After being correlated with geological data, it is interpreted that the lithology in the A-A' profile in the north of the research area is crystalline bedrock (3.3 g/cm$^3$), pre-rift rock is sandstone (2.9 g/cm$^3$) and shale. (2.82 g/cm$^3$), rocks deposited during the syn-rift are shale (2.88 g/cm$^3$) and sandstone (2.3 g/cm$^3$), and rocks deposited during the late rift are carbonate rocks (2.4 g/cm$^3$) and halite/massive salt (2.67 g/cm$^3$).

Throughout the Red Sea and its surroundings, gravity anomaly values show a buildup of sedimentation with an average density of 2.2 g/cm$^3$, oceanic crust below the main trench with an average density of 2.9 g/cm$^3$, intermediate crust flanking the oceanic crust with an even density. -average 2.85 g/cm$^3$ (**Figure 3**). In inverse modeling, the thickness of the oceanic crust varies from 40 km to 15 km, approaching transitional crust and oceanic crust.

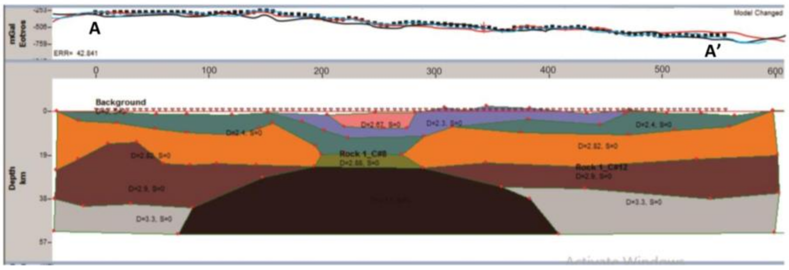



**Figure 3**. 2D model of profile A-A’

Profile B-B' (**Figure 4**) is located in Massawa and Jizza across the southern Red Sea and the Ethiopian plateau across the Afar depression between Dessi to Assab. The oceanic crust is associated with the southern Red Sea axial trough with a model density of 2.88 g/cm$^3$. Sebai et al (1991) interpreted that the continental crust extends across the southern Red Sea as a result of the crust being stretched and intruded by the upper mantle.

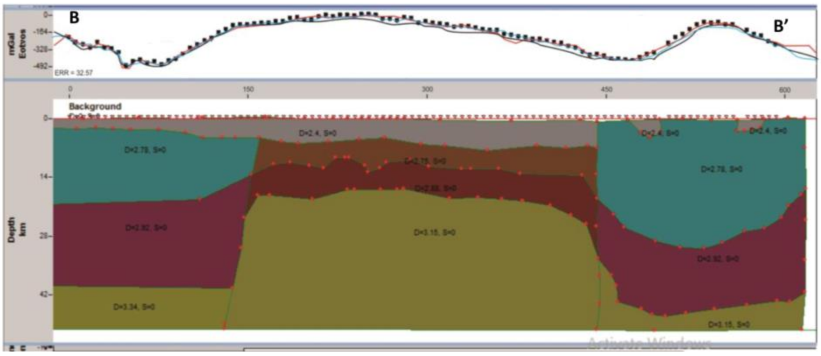



**Figure 4**. 2D model of profile B-B’

After being correlated with geological data, it is interpreted that the lithology in the B-B' profile in the south of the research area is crust (3.34 g/cm3), crystalline bedrock (3.15 g/cm3), pre-rift rock in the form of sandstone (2.88 g/cm3) and carbonate rocks (2.92 g/cm3), rocks deposited during syn-rift in the form of shale (2.75 g/cm3) and marl/marl (2.78 g/cm3), and rocks deposited during the late rift are carbonate rocks (2.4 g/cm3).

In both models A-A' passes through the African shield (off the coast of Egypt) and the northern Red Sea and B-B' crosses the southern Red Sea in the Danakil depression. In the A-A' model, it shows that the eastern side of the northern Red Sea, the continental crust experienced thinning where the density of the continental crust at the beginning of the Miocene formed a western valley. The B-B' model shows stretching and thinning of the continental crust in the southern Red Sea and Danakil depression. Positive gravity anomaly values elongated in the northwest are interpreted as dense oceanic crust and magma intrusion into stretched continental crust (Makris, 1991).

**Tectonic Model**

***Pure Shear Model***

The extension that occurs in the Red Sea occurs due to convection flows in the athenosphere (**Figure 5)**. Extension that occurred during the Oligocene resulted in thinning of the lithosphere layer associated with normal faults in the southern Red Sea. The occurrence of continuous rifting and thinning is the result of subsidence tectonics and the development of horsts and grabens with sloping blocks towards the development of Miocene marine inclusions. The upper layer of the continental crust thinned and fractured, giving way to the intrusion of oceanic basalt at 4 million years.

Martinez and Cochran (1988) modeled an extensional model where each part of the Red Sea (North, South and Central) had a different phase in the rifting process and continental margin growth (**Figures 6a** and **Figure 6b**).

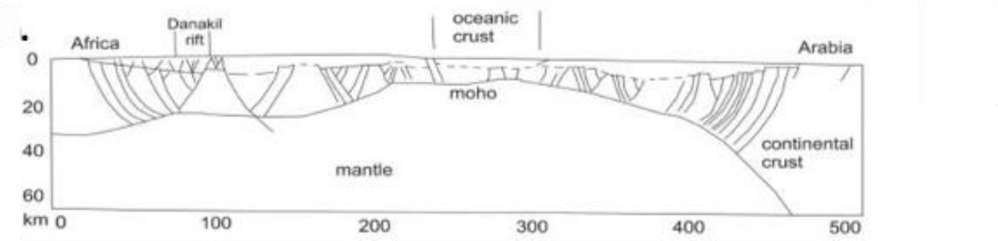
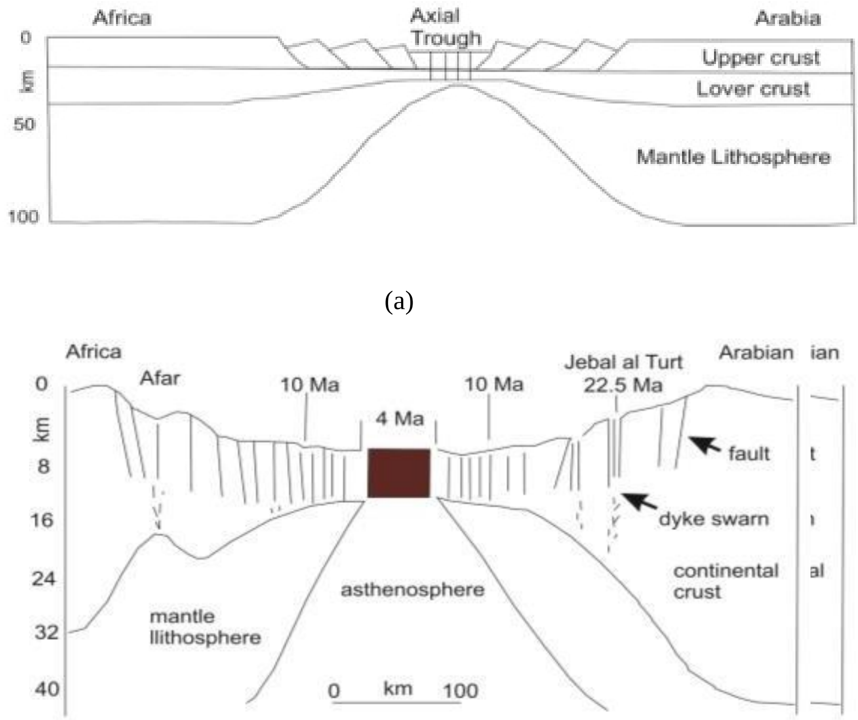



**Figure 5.** The extension of Red Sea occurs due to convection flows in the athenosphere




(a)

(b)

**Figure 6.** Extensional model in rifting process and continental margin growth

The extensional evolution of the Red Sea marks the late Oligocene or early Miocene period which is characterized by the presence of normal faults and the formation of Miocene dyke followed by the beginning of seafloor spreading in the axial trough of the southern Red Sea in the last 5 million years. The expansion center spread northward and through a transition zone centered on the central part of the Red Sea. The spreading of the ocean floor influenced the formation of the northern Red Sea where the formation of new oceanic crust and the separation of Arabia and Africa influenced the process of extension and thinning of the continental crust. According to Berhe (1986), the development phase of the rifting model that occurred in the southern Red Sea takes into account the dike formation process in southern Saudi Arabia (Tihama Asir Complex) and age tracing based on K-Ar in the southern Afar basin (14-11, 11-10, 9 -7, 5-7 and 1.6 million year) (**Figure 7**).

The beginning of the process of continental separation in the Red Sea occurred when a north-east trending drift zone was formed. Then there is the development of extension which forms normal faults and the formation of dikes in the continental crust accretion system. The continuous occurrence of basaltic volcanism in the Afar is evidence of the second phase of ocean floor rifting in the Red Sea. In this second phase, the process of forming a fault zone occurred during the African-Arabian separation process which formed the Red Sea, but there is no strong evidence of its gradual formation (Berhe, 1986). Basalt dikes in the Tihama Asir complex show an early phase of dike intrusion related to the rapid process of thinning of continental crust near the coastline and only forming oceanic crust in the Red Sea.

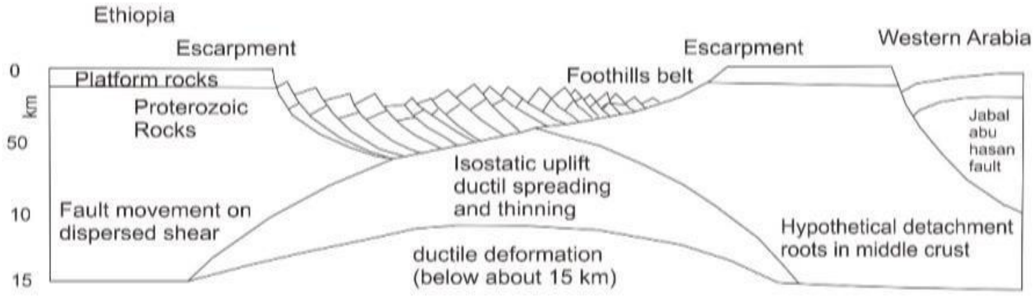



**Figure 7.** The development phase of the rifting model that occurred in the southern Red Sea

***Simple Shear Model***

**Figure8** shows the volcanism in the Oligocene (Afar plum) is a sign of the beginning of mantle upwelling and magmatic underplating. Volcanism that occurred in the early to middle Miocene along the Arabian plate illustrates the cessation of shear zone formation. This model is used to determine the asymmetry distribution of volcanic rocks and highlands (± 3km) along the Arabian side of the Red Sea compared to along the African side with low elevation (± 2 km).

Meshref (1990) said that the eastern flank of the Red Sea could be formed due to thermal processes described in the asymmetric model. The use of a simplified kinematic model wherethe initial stretching of the lithosphere and uplift of the athenosphere and lowering of therift results in high density rocks being uplifted. The initial phase of stretching is followed by isostatic adjustment in response to lateral mantle flow. Meshref (1990) stated that the asymmetry model became more visible in the final phase of ocean formation, so it is assumed that the spreading/separation of the ocean floor occurred along the Red Sea.

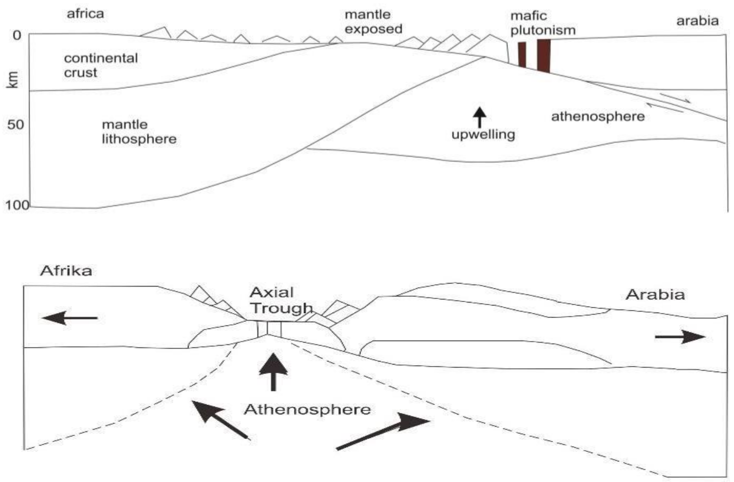



**Figure 8**. Simple shear tectonic model

***Pull Apart Model***

The occurrence of strike-slip along this fault system (**Figure 9**) resulted in the formation of sharp plate boundaries which resulted in a decrease in the extension process and thinning of the continental crust at the end of the Oligocene. This change was followed by the expansion of the continental crust and faulting in the bedrock of the Gulf of Suez around 19-15 million years, which experienced an extension of 5 mm/year (Coulie et al., 2003). Crustal elongation in the Suez buckle stagnated at 15 million years and extension decreased <1 mm/yr.

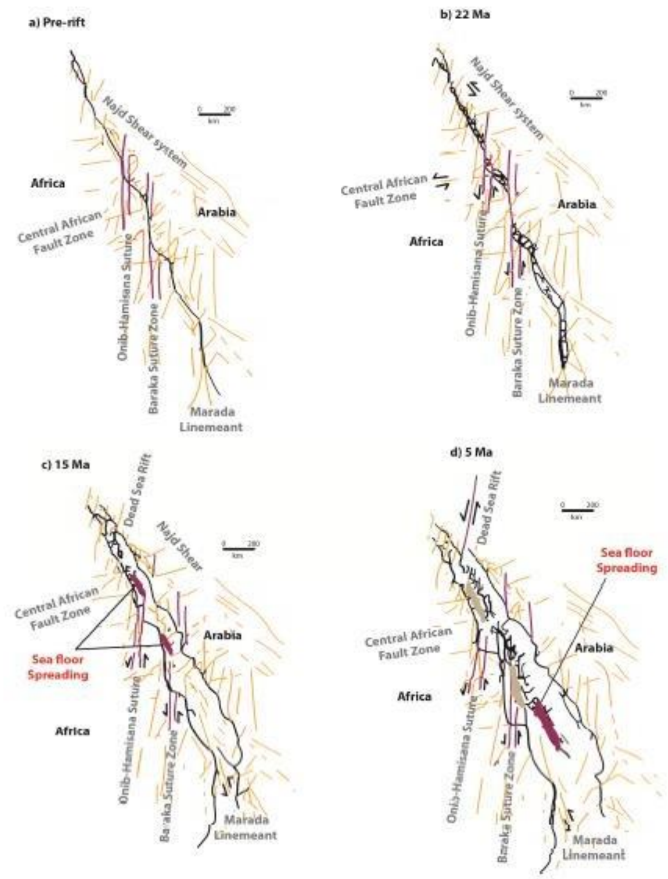



**Figure 9**. Pull apart model

Sticke-slip movement in the Gulf of Aqaba influences fault processes in the northern and central parts of the Red Sea. Stike-slip movements were influential in Egypt and along the coast of Sudan, while Arabia separated from Africa due to the formation of continental crust during the early development of the pull apart basin. The final stage of this tectonic model is the spreading of the ocean floor which occurs in the south towards the north of the Red Sea (Markis, 1991).

## IV. CONCLUSIONS

Based on this research, conclusions can bedrawn: the pulling of the A-A' profile due to the gravity gradient between the Red Sea and the Arabian shield is related to rifting of the continental crust at the edge of the rift margin or when the Arabian shelf is beneath the crust. Profile B-B' is located in Massawa and Jizza across the southern part of the Red Sea and the Ethiopian highlands across the Afar depression between Dessi to Assab. Both profiles A-A' and B-B' both describe the presence of lithology in the form of crystalline bedrock, carbonate rock, sandstone and shale. The difference in the two model results can be seen in the formation of halite/massive salt in the A-A' model, while in B-B' the formation of marl/marl occurs in the syn-rift.

The simple shear model aims to look at the smallest angle of dipping detachment of the Red Sea to explain the basin geometry and magmatism that occurs in the Arabian flank rift. The pull apart model explains asymmetric topography and magmatism. The technical evolution of the Red Sea has been compared to the Wilson cycle that produced a young ocean basin. The rifting model can be created using the simple shear model, pure shear model, and pull-apart basin. If we look at the suitability of geological and geophysical data (gravity data and models), the rifting that occurs is caused by the time and initial extension process of basin formation, the mafic magma system, tectonic forces that influence rifting and crustal expansion.

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