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Review article

Seafloor spreading of the third arm of the Afar triple junction: A review

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A B S T R A C T

The only place within the East African Rift System where seafloor spreading is being manifested along with new crust being formed is at the Afar triple junction, a seismically active area defined by latitude 9°N to 14°N and longitude 43E° to 49E°. Previous seafloor spreading studies have primarily concentrated on the Aden-Owen Carlsberg Ridge (AOCR). The AOCR defines the boundary between the Eastern Gulf of Aden and the Western Gulf of Aden. Although the previous studies have provided insight into seafloor spreading rates, the timing of seafloor spreading, particularly in the Western Gulf of Aden (encompassing the study area) remains unclear. This study seeks to estimate the rates of seafloor spreading by reviewing data from previous studies and integrating geophysical (paleomagnetic anomalies), geological data and systematically estimating seafloor spreading rates and determining the timing of the initial seafloor spreading in the Afar region using advanced geo-software (Gplates). The results from our modeling show that the initial seafloor spreading began approximately 16 million years ago, with spreading rates varying from 12.29 to 20.12 mm/yr (average = 15.75 mm/yr). The average seafloor spreading rates in the study area are nearly 1.5-fold lower than the average seafloor spreading in the Eastern Gulf of Aden (23 mm/yr). The predominant seafloor spreading in the study area is East-West. Further, the angular rotation of the Somalian plate against the Arabian plate has been estimated to be 0.5353°/Ma. The study enhances understanding of plate tectonics, seismic hazards, volcanism and hydrocarbon systems in the Afar region.

1. Introduction

Seafloor spreading refers to the movement of lithospheric plates that results in the formation of new oceanic crust at mid-ocean ridges [1] Seafloor spreading is studied through paleomagnetic studies by examining the alternating patterns of magnetic polarity preserved in seafloor rocks. Through paleomagnetic analysis, seafloor models are constructed based on the geomagnetic reference timescale, providing substantial evidence of variations in Earth's magnetic field over time [2]. This chronologically precise timescale enables scientists to discern distinct magnetic anomalies within the seafloor, each corresponding to specific periods in Earth's history. According to Ogg (2020), a "chron" designates a period in geological records characterized by its magnetic polarity. A chron is considered to have "normal polarity" if the orientation of the geomagnetic field aligns with the present dipole polarity. On the other hand, a chron is classified as having "reversed polarity" when the orientation of the geomagnetic field is opposite to the present dipole polarity [3]. The paleomagnetic analysis also aids in determining the age of the seafloor. Furthermore, seafloor spreading contributes

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to geochronology by establishing a timeline of seafloor events and assisting in dating other geological phenomena such as volcanic eruptions and magnetic inversions [4]. Additionally, studying the deformation of the Earth's crust associated with seafloor spreading aids in comprehending tectonic boundaries and identifying different types of plate boundaries [5]. Seafloor spreading has significantly evolved since the mid-20th century when it was introduced. Heirtzler [6] examined the groundbreaking idea that was introduced by Harry Hess during the early 1960s which suggests that the ocean floor wasn't static but instead diverging along mid-ocean ridges. This proposition challenged the prevailing view of a stationary Earth's crust and provided a scientific explanation for continental drift. The work highlighted the confirmation of mid-ocean ridges through oceanographic expeditions and sonar mapping techniques, where new oceanic crust was forming as magma upwelled from the mantle. Also, magnetic anomalies on the ocean floor, alternating between normal and reversed polarity, provided compelling evidence for sea-floor spreading, correlation with the age of oceanic crust. In September 1963, Vine and Mathews [7] conducted a comprehensive survey across the northwest Indian and North Atlantic oceans as part of the Ocean Drilling Program. Their work revealed significant findings, showing that the foothills of the ridge exhibited long-period anomalies, while the flanks of the ridge displayed short-period magnetic anomalies. Positive anomalies were found to be associated with mountains on either side of the valley, while negative anomalies represented depressions in the bottom topography, indicating the median valley of the ridge. High-resolution bathymetric surveys utilizing sonar technology have played a pivotal role in mapping ocean floors and revealing vital features related to seafloor spreading [8]. By the 1970s, it became evident that sea-floor spreading was intricately linked to mid-ocean ridges and the creation of oceanic crust and upper mantle within them [9].

The Afar region, located at the junction of the Arabian, Nubian and Somalian plates, is a geologically complex area with intense tectonic activity (s) including seafloor spreading [10]. The area is characterized by active spreading centers and volcanic activity, making it an ideal location to study seafloor spreading and plate motions [11]. In this context, the seafloor rates of the Afar region, particularly those involving the third arm comprising of Arabian and Somalian plates, have garnered significant attention in recent research [12]. The Somalian and Arabian plates exhibit relative motions (slip rates) over geological time [13]. These slip rates aid in quantifying seafloor spreading in the Afar region. The Gulf of Aden therefore serves as a reference point for assessing the spreading rates in the Afar region.

The seafloor spreading history of the 3rd arm of the Afar triple junction, primarily located in the western part of the Gulf of Aden and defined by latitude 9°N to 14°N and longitude 43E° to 49E°, has been provided by Girdler [14]. The work of Girdler [14] on the western Gulf of Aden, provides substantial evidence on the formation of the new oceanic crust through tectonic plate separation. This evidence is supported by geophysical surveys, satellite navigation and inferences from the spreading model of Laughton [15]. East of the study area (i.e., outside the Afar region), Fournier [16] presents a comprehensive study on the kinematics of the Arabian-Somalian plates over the past 20 Ma by integrating novel geophysical data from the Aden-Owen-Carlsberg triple junction with existing magnetic data from the Gulf of Aden. The research primarily focuses on the initiation of the Gulf of Aden, characterized by the substantial penetration of the Sheba Ridge towards the African continent and the development of the triple junction [17]. Magnetic data analysis

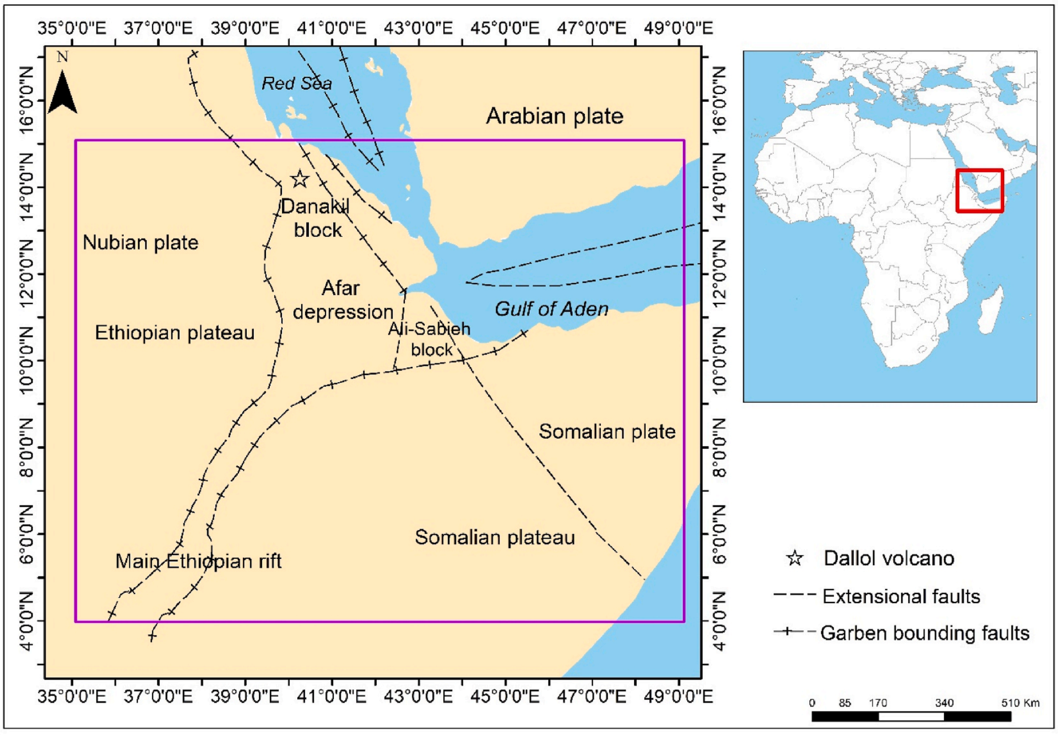

Fig. 1. - Simplified tectonic map Afar region. Adapted from Cavalazzi [40].

reveals a three-phase progression of Sheba Ridge propagation, originating from the east and advancing westward. The study suggests that seafloor spreading initiated ~20 Ma, yielding a new oceanic crust. Notably, from 20 Ma to 16 Ma, the Sheba Ridge exhibited astonishing propagation of 1400 km at an average rate of 35 cm per year, driven by the rotation of the Arabia-Somalia rigid plate. Following the Chron 5C stage at 16.0 Ma, the spreading rate displayed a rapid decline and then gradually decreased until around 10 Ma. Despite previous studies conducted by Girdler [14] and Fournier [16] to map the third arm of the Afar region, aiming at understanding the geological history of the western Aden region and the development of the Aden-Owen Carlsberg ridge respectively, the precise rate of oceanic spreading remains a challenge. Therefore, the precise oceanic spreading rate of the Afar region has not been systematically established [18]. With the advancements in science and technology, we chose to integrate various data sources on this area, incorporating the seafloor history documented by Girdler and Styles [14], alongside information from Fournier [16], Seton [19] and Müller [20].The integration is strengthened through the supplementation of bathymetry from GEBCO database and magnetic anomalies from Earth Byte database. All the information were integrated into the GPlates software to establish the precise seafloor history which includes the estimation of the timing of initial seafloor spreading in the area. In our model, the closure of a triple junction is governed by specific assumptions and rules outlined in Ref. [21], which include: (i) considering ridge axes as perpendicular to the spreading direction, (ii) treating transform faults as purely strike-slip features, (iii) assuming rigid plates and stable triple junctions (i.e., ridge-ridge-ridge) and (iv) considering seafloor spreading to be symmetrical.

2. Geological setting

The Afar region has experienced complex and dynamic interactions between volcanic and tectonic processes from the Miocene to the present [22]. The Afar area is characterized by extended lithosphere and low surface topography, bordered by the Ethiopian Plateau, Somalian Plateau, Danakil and Ali-Sabieh Blocks to the northeast and East respectively (Fig. 1). The Afar area's development commenced with the eruption of vast flood basalts around 30 Ma [23]. The rifting of the Afar region began at ca.19 Ma [24] The Arabian plate moved primarily towards the northeast and later rotated counterclockwise by over 40° towards the north-northwest. The Somalian plate initially moved south-southeast but underwent a counterclockwise rotation of nearly 40° towards the east. Continental rifting was succeeded by oceanic spreading ~17.6 Ma in the easternmost part of the Gulf of Aden, progressing westward thereafter. Seafloor spreading in the central and southern Red Sea is estimated to have occurred in ~5 Ma [25], with possible initiation as early as 12 Ma.

The Main Ethiopian rift emerged to the south of Afar, shaping the 3rd arm of the current triple junction (Fig. 1), while the movement of the Somalian plate away from the Nubian plate likely began at 19 Ma [24]. The Danakil Block evolved into an additional conjugate margin to the Western Afar Margin (WAM) ~11 Ma [26]. The distribution of strain between the rifts on both sides of the microplate could have played a role in the prolonged process of break-up in Afar. As extension continued, the deformation transitioned from the Western Afar Margin (WAM) to the rift axes, and both magmatism and the deformation became highly concentrated along

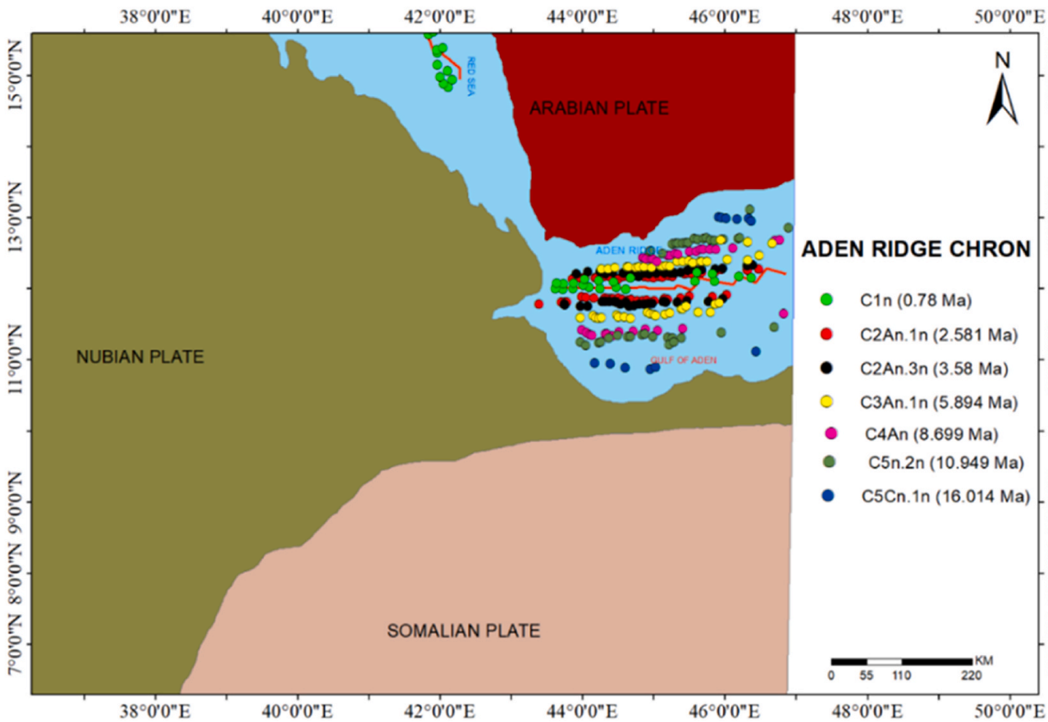

Fig. 2. -The Aden Ridge Magnetic data,obtained from Fournier [17]and The modified map after Schaegis [41].

distinct segments established around 2 Ma [27]. These segments evolved around the same time as the Gulf of Aden system extended into Afar through the Gulf of Tadjoura, and they can be considered as the sites of embryonic oceanic spreading centers and the focal points of ongoing continental break-up processes [18].

The rifting episodes have played a crucial role in the formation of sedimentary basins from the edges of the Afar triple junction to the currently active sections, notably including Lakes Asal and Afrera [28]. The geological conditions have favored the development of extensively deep, enclosed lakes in the central Afar area since the late Pliocene epoch (ca.2.5 Ma). Sediment distribution (Fig. 1) indicates a chronological progression of basin development from southwest to northeast and a shift in the orientation of prominent active faults from roughly east-west to northwest ca. 1.4 Ma [29].

3. Methodology

We reconstruct the history of seafloor spreading and continental motions, with the Aden Ridge serving as the reference frame. Magnetic anomaly data and finite rotations from Fournier [16] and the Earth Byte website (https://www.earthbyte.org/category/resources/data-models/paleomagnetic-data/) were employed (Fig. 2). Additionally, bathymetric data from the GEBCO database (Fig. 3), GPlates geo-data that encompass geophysical numerical raster data (sea age grid) from Seton [19], and field-magnetic anomaly data from the NOAA database were incorporated to complement the magnetic data. Seafloor model reconstruction was performed using the GPlates software available at https://www.gplates.org. The deformation network method, based on an established plate kinematic model and mathematical algorithms implemented within GPlates, was utilized to determine the seafloor rates along the third arm of the Afar triple junction (i.e., the boundary separating the Arabian and Somalian plates).

The utilization of multiple data sources in GPlates for seafloor model reconstruction in the Afar region has limitations that were considered. These include potential uncertainties arising from the resolution and accuracy of the data, and challenges in integrating diverse datasets—such as when one dataset has high spatial resolution but low temporal coverage, while another dataset has the opposite characteristics, making reconciliation difficult due to the need for assumptions or simplifications that may not accurately reflect real-world complexities—reliance on assumptions and simplifications in the modeling process, limited data coverage in certain areas, and the snapshot nature of the reconstructed model, which may not capture all temporal variations or complex interactions within the region. These limitations were taken into account and inferences made from the geomagnetic reversal time scale of Cande [30], as well as conclusions drawn from the previous studies of Girdler [14], Cochran [31] and Daniels [32].

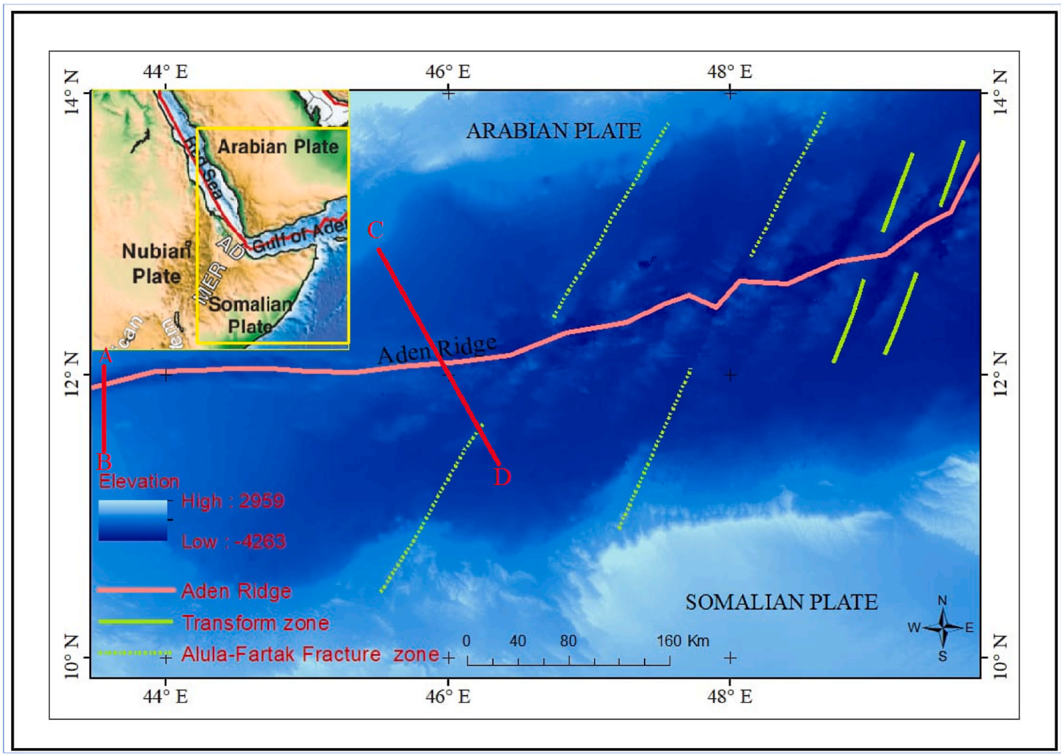

Fig. 3. Bathymetry map with bathymetry profiles across Gulf of Aden. Depths are presented in meters

Table 1
The Afar spreading rates.

Time (Ma)	Latitude (°N)	Longitude (E°)	Spreading rates (mm/yr)
65	12.3141	37.3057	0
64	12.3141	37.3057	0
63	12.3141	37.3057	0
62	12.3141	37.3057	0
61	12.3141	37.3057	0
60	12.3141	37.3057	0
59	12.3141	37.3057	0
58	12.3141	37.3057	0
57	12.3141	37.3057	0
56	12.3141	37.3057	0
55	12.3141	37.3057	0
54	12.3141	37.3057	0
53	12.3141	37.3057	0
52	12.3141	37.3057	0
51	12.3141	37.3057	0
50	12.3141	37.3057	0
49	12.3141	37.3057	0
48	12.3141	37.3057	0
47	12.3141	37.3057	0
46	12.3141	37.3057	0
45	12.3141	37.3057	0
44	12.3141	37.3057	0
43	12.3141	37.3057	0
42	12.3141	37.3057	0
41	12.3141	37.3057	0
40	12.3141	37.3057	0
39	12.3141	37.3057	0
38	12.3141	37.3057	0
37	12.3141	37.3057	0
36	12.3141	37.3057	0
35	12.3141	37.3057	0
34	12.3141	37.3057	0
33	12.3141	37.3057	0
32	12.3141	37.3057	0
31	12.3141	37.3057	0
30	12.3141	37.3057	0
29	12.3141	37.3057	0
28	12.3141	37.3057	0
27	12.3141	37.3057	0
26	12.3141	37.3057	0
25	12.3141	37.3057	0
24	12.3141	37.3057	0
23	12.3141	37.3057	0
22	12.3141	37.3057	0
21	12.3141	37.3057	0
20	12.3141	37.3057	0
19	12.3141	37.3057	0
18	12.3141	37.3057	0
17	12.3141	37.3057	0
16	11.6908	36.9837	15.547
15	11.5971	36.8444	18.862
14	11.5042	36.7046	19.947
13	11.4122	36.5642	20.122
12	11.321	36.4233	19.518
11	11.2307	36.2818	18.427
10	11.149	36.1623	17.922
9	11.0679	36.0425	17.417
8	11.0154	35.9601	15.877
7	10.9706	35.8867	14.079
6	10.9266	35.813	12.28
5	10.8428	35.6796	12.563
4	10.7597	35.5458	12.845
3	10.7356	35.4401	12.964
2	10.6966	35.355	13.132
1	10.6215	35.2706	13.67
0	10.5469	35.1857	12.655

4. Results

4.1. Seafloor spreading rates

A comprehensive overview of slip rates spanning from 65 Ma to the Present day is provided in Table 1. The animation presented in the Afar region reveals that seafloor spreading started at 16 Ma, and the Somalian plate moves southeast at 1.17 mm/yr relative to the fixed Arabian plate, demonstrating a predominant southeastward shift. Before 16 Ma, there was no indication of seafloor spreading.

The seafloor spreading in Afar started at ca.16 Ma with a spreading rate of 15.547 mm/yr that increased to 20.12 mm/yr at ca. 13 Ma. From ca. 13 Ma to ca. 6 Ma, slip rates drastically decreased from 20.12 mm/yr to 12.28 mm/yr During this period of 7 million years, the phenomenon is likely due to the deceleration of the relative motion of the Arabian and Somalian plates. From ca. 6 Ma to ca. 1 Ma, the spreading rates generally remained constant at a mean rate of 12.91 mm/yr. At the present day, the estimated seafloor spreading rate at the Afar region is 12.655 mm/yr (Table 1 & Fig. 4**)**. The results suggest that seafloor spreading rates of the western Gulf of Aden varied between 12.28 mm/yr and 20.12 mm/yr.

From the constructed seafloor spreading and rifting model, the initial stages of seafloor spreading are marked by the appearance of Chron 5, represented by C5cn.1n (16.014 Ma) and C5n.2n (10.949 Ma). These chrons discerned through magnetic picks and anomaly raster data, signify the commencement of divergent tectonic forces that herald the onset of seafloor opening, notably, the manifestation of Chron 4 (C4An) at 8.699 Ma, a pivotal phase, characterized by a dense display of magnetic anomalies indication of high seafloor spreading rates (Fig. 2). This intensified spreading could be attributed probable by heightened tectonic activity and enhanced plate divergence. Subsequently, Chron 3 (C2An.3n) emerges approximately 20 km away from the Aden ridge, reflecting the continuous expansion of seafloor spreading as rift propagation persists. The appearance of Chron 2 (C2An.1n) at 2.581 Ma, although less densely manifested, suggests a reduction in spreading rates, potentially due to evolving tectonic forces or reduced velocities of the moving plates. Lastly, the proximity of the youngest Chron 1 (i.e., Cn. ln at 0.78 Ma) to the Aden Ridge indicates ongoing seafloor formation near the ridge (Fig. 5).

It was also noted that the seafloor spreading is more pronounced towards the African continent, covering approximately 170.67 km, compared to the Arabian side, which covers 138.03 km. The calculated rates attest to seafloor spreading rates of 10.67 mm/yr to the eastern region and a rate of 8.67 mm/yr to the western region as shown in Fig. 2.

The bathymetry profiles, marked as AB and CD at 43E° and 47E° across the Aden Ridge (Fig. 3), display deeper median valleys (Figs. 6 and 7). The data also reveals a deformed zone between the Shukra-El-Sheik Fracture Zone (SSFZ) and the Alula-Fartak Fracture Zone (AFFZ), as shown in Fig. 9. This is further supported by the segmented nature of the Aden Ridge.

The sea age grid was applied to the Afar region, revealing that the crust in this area is relatively young (i.e., 16 Ma) as shown in Fig. 8.

It was observed, through a model and a depiction adapted from Bollino [33], that seafloor spreading features of revealed plate motion directions and highlighted significant fracture zones such as SSFZ and AFFZ within the Gulf of Aden (Fig. 9).

The magnetic anomaly profiles 375 (AB) and 3502 (A′B′) oriented in a northwest to-southeast direction were plotted across the western part of the Aden Ridge (spanning an area from 43E° and 49E and a continuous sequence from anomaly 1 to anomaly 5 as revealed in Fig. 5. The largest anomaly in Profile 375 (Fig. 10) appears over a width of hardly 100 km. Profile A′B′ on track line 3502 shows two significant magnetic anomalies encircled in Fig. 11 as N and M with anomaly widths of about 125 km each. Such widths give clues about the size of the new oceanic crust being formed at the spreading ridge (western section of the Aden Ridge) and the submarine canyons. Beyond anomaly 5, there is a significant decrease in the amplitude of the magnetic anomalies corresponding to a magnetic quiet zone. The magnetic profiles show negative magnetic anomalies that correspond to the median valley i.e., the mid-oceanic ridge and positive magnetic anomalies that correspond to the mid-oceanic flanks. These flanks have crests with reduced

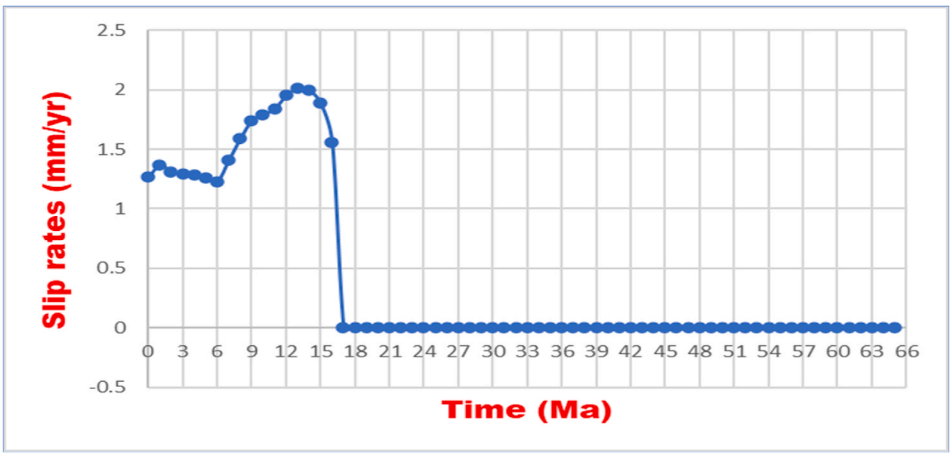

Fig. 4. The Slip rates of the third arm of the Afar triple junction

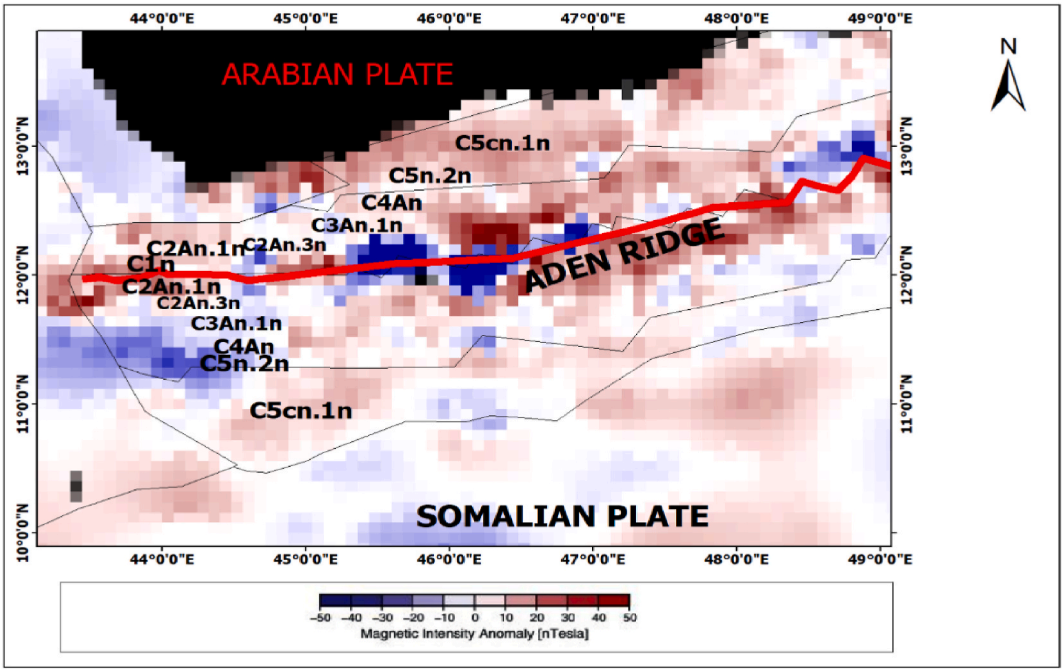

Fig. 5. The magnetic anomalies used for reconstruction. clear magnetic anomaly sequence is noticed corresponding to anomalies C1n to C5cn.1n

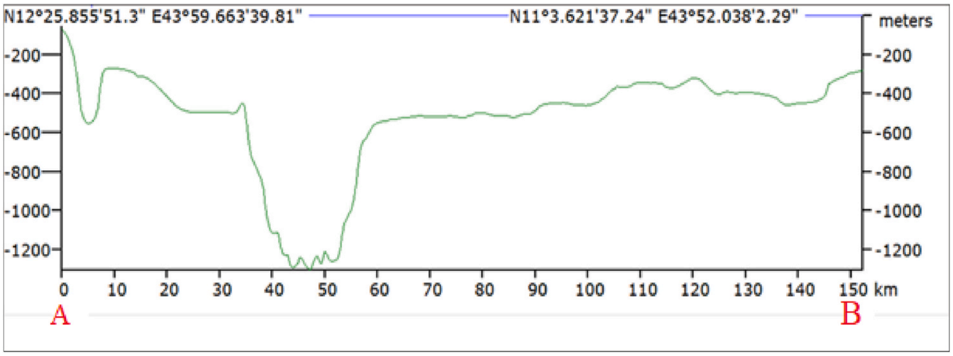

Fig. 6. The Bathymetry Profile across The Aden ridge (at 43 E°)

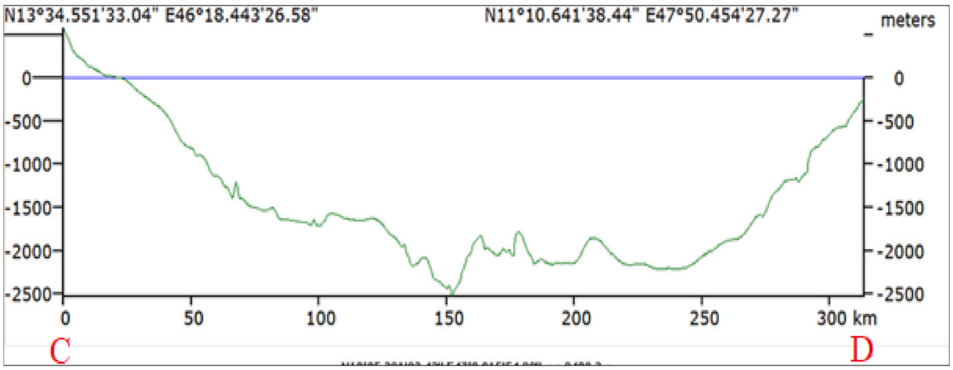

Fig. 7. -The bathymetry profile across Aden ridge (at 47E°)

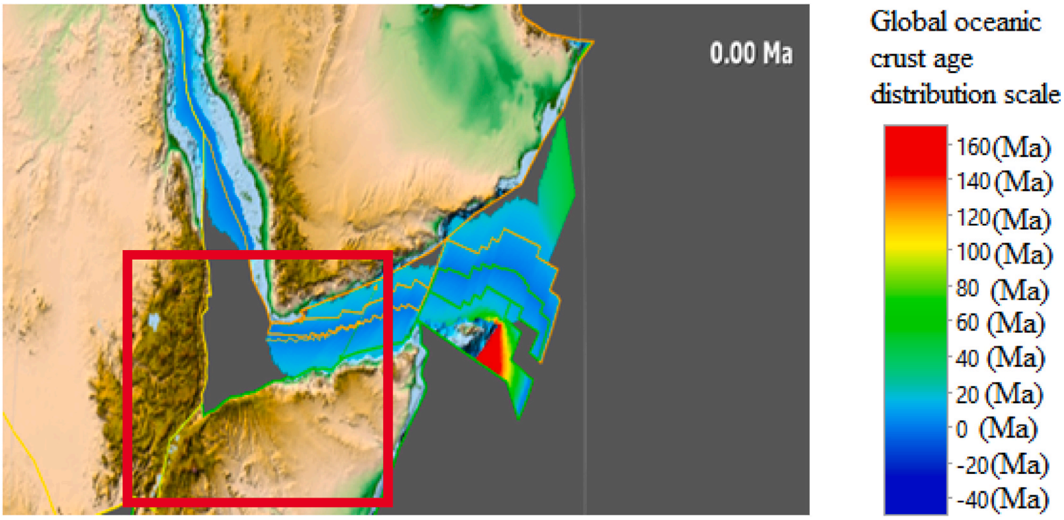

Fig. 8. - The Present age sea grid in the Afar region from the work of Seton [19].

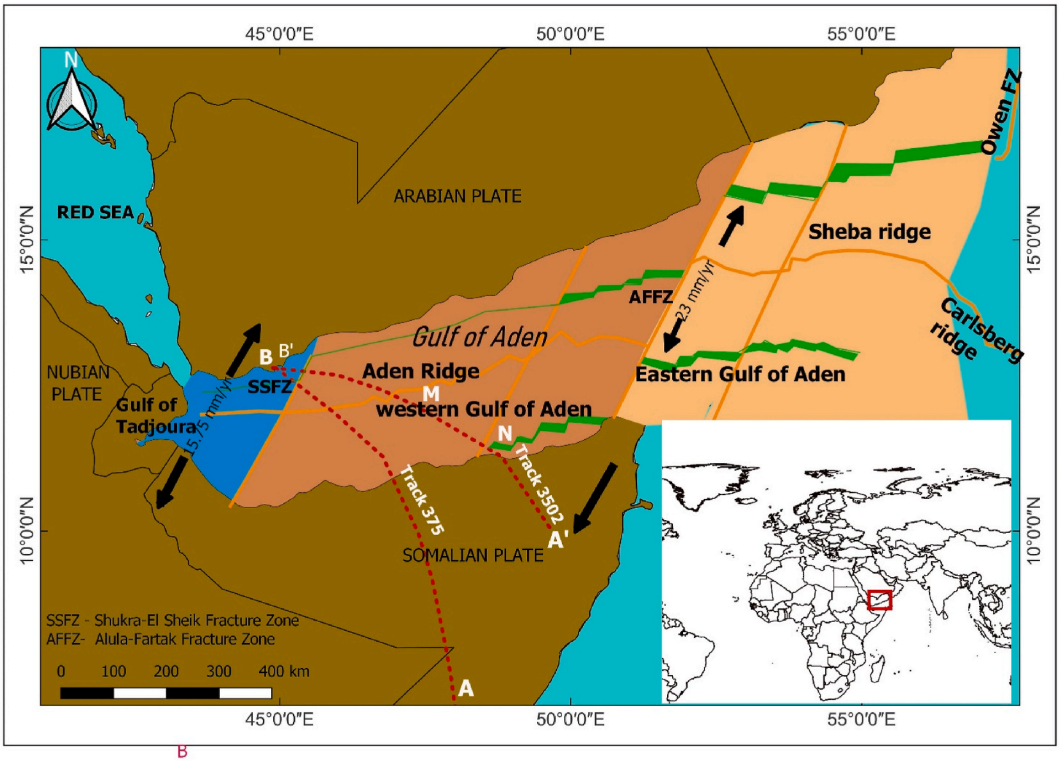

Fig. 9. - The seafloor spreading features in the Gulf of Aden as modified from Regorda [33]Large black arrows indicate the directions of plate motion in the region. SSFZ: Shukra-el-Sheik fracture zone. AFFZ: Alula-Fartak fracture zone. Blue and coral colors indicate the western Gulf of Aden, while the bronze color indicates the eastern Gulf of Aden. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

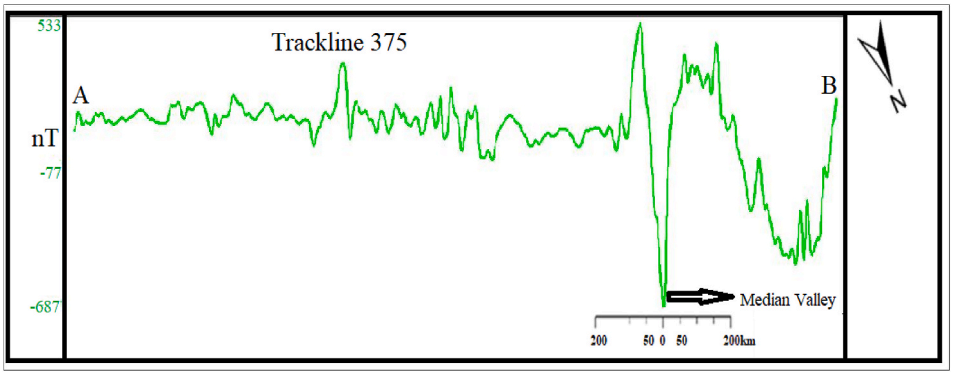

Fig. 10. Magnetic profile along track 375

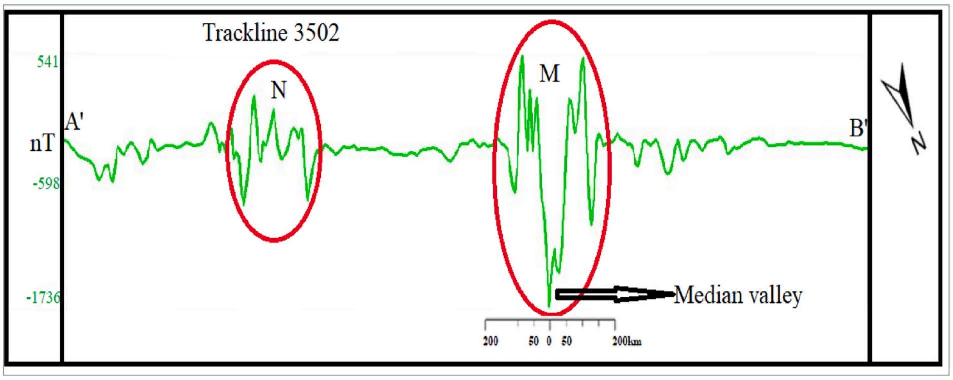

Fig. 11. Magnetic anomaly profle along track 3502

amplitudes away from the ridge. Profile 3502 shows small delict features and a general depression at the center part indicating a significant decrease in the amplitudes away from the depression (Fig. 11).

5. Discussion

The seafloor spreading rates and kinematics of the third arm (i.e., the sea floor slip rates of Arabia and Somalia in x and y vector directions) from Paleogene to the Present stated that rifting started at ca.19 Ma [34]. Analysis of magnetic anomalies indicates that seafloor spreading commenced in the eastern Gulf of Aden in an ENE-WSW direction within the Afar region, near the E-W trending Sheba Ridge, and extended westward into the western Gulf of Aden around 16 Ma, as depicted in Fig. 9. This led to the development of anomaly 5 and the formation of the third portion of the Sheba ridge within the western Gulf of Aden. This deformed part lies between the Alula-Fartak fracture zone and the Shukra-EL-Sheik fracture zone as illustrated in Fig. 9 [17]. The Gulf of Aden, located between the Gulf of Tadjoura and the Shukra-El Sheik Fracture zone, is a relatively youthful and narrow oceanic basin that was formed during the Miocene Epoch [35]. It resulted from the gradual separation of the Arabian and Somalian tectonic plates across rifted margins. The basin has an average orientation of approximately N75°E making an angle of 50° to the N25°E from the sea floor spreading (opening) direction and is influenced by the active Afar hotspot during the initial stages of rifting. However, the western margins of the Afar region are obscured by young lavas originating from the Afar mantle plume during the Oligo-Miocene [36]. The geomagnetic field characteristics within the Gulf of Aden have previously been studied by Laughton [15] and Girdler [14]. However, since the 1970s, more magnetic data from the works of d'Acremont [37] and Fournier [16] have become available, allowing us to analyze the magnetic anomaly profiles of the western components of the Gulf of Aden. The magnetic anomalies exhibit linear trends along the western Gulf of Aden oriented E-W direction. Typically, transform faults crossing mid-ocean ridges in a NE-SW direction **as shown in** Fig. 3; 7, defining a belt of reduced magnetic relief in this region as supported by Vine [7].

Our results are in line with the thermal model of Daniels [32], which was able to reveal the influence of dyke intrusion on the extension of the Afar region, causing a faster extension rate of 16 mm/yr in the Red Sea rift. Also, the work of Bollino [33] confirms the spreading rate in the western Gulf of Aden to be 13 mm/yr and 23 mm/yr in the eastern Gulf of Aden. However our study, contracts with the study of Girdler [14] that provide an interpretation of magnetic data gathered from closely spaced tracks in the western Aden region that suggest that the formation of the Gulf of Aden down-warp commenced approximately 40 Ma accompanied by seafloor spreading that took place in two distinct phases. During the first phase, spanning from 30 Ma to around 15 Ma, followed by a hiatus of approximately 10 Ma. Subsequently, the second stage of spreading began approximately 5 Ma and that it has continued to the Present day. Their findings raise controversies since most of scientists record rifting initiation at 20–25 Ma. Does this imply seafloor spreading starting before lithospheric rifting in the Afar region at ~20–25 Ma as per Gidler, Beyene and Demets [12,38,39]? Our model affirms that the seafloor spreading in the Afar region started ca.16 Ma and the established slip rates suggests that the region is slowly transitioning from the continental lithosphere to an oceanic crust at an average rate of 15.75 mm/yr.

The analysis also indicates that the pole of opening between Somalia and Arabia did not undergo significant changes during the seafloor spreading from 16 Ma to the Present as evidenced by the change from 11.6908 °N/36.9837 E° to 10.5469 °N/35.1857 E° (Table 1). Based on the calculated average rates (i.e., 0.07149375°/Ma in latitude and 0.112375°/Ma in longitude) - the movement between the two plates seems to be relatively slow (Table 1). The propagation process is attributed to the rotation of Arabia and Somalia, around a relatively fixed pole positioned at 12.5631°N and −48.3352 W° of the propagating Aden ridge. The asymmetrical distribution of seafloor spreading, with a greater extension of approximately 170.67 km towards the African continent compared to 138.03 km towards the Arabian continent (Fig. 2). These variations suggest diverse geological conditions that influence Afar sedimentary basin formation. The spreading rate of about 15.75 mm/yr (Fig. 9) near the African plate can lead to high sediment accumulation creating favorable hydrocarbon reservoirs. The associated tectonic interactions can create structural traps for hydrocarbon migration and entrapment. The resulting marine topography impacts influence reservoir quality and distribution. The heightened tectonic activity from increased rift spreading may facilitate hydrothermal processes controlling hydrocarbon generation and migration.

The juvenile oceanic crust in the Afar region attests to the ongoing seafloor spreading and substantial volcanic activity associated with the dynamic tectonic activities within the Afar region, contributing to the current kinematics along the East African Rift. The youthfulness of the oceanic crust is presumably also attributed to the manifestation of oceanic crust around ca. 16 Ma. This resulted in the Aden ridge propagation from the eastern Gulf of Aden at approximately ca. 17.6 Ma [17]. Therefore, such young crust in the Afar region is a clear indication of the tectonic dynamism, signifying ongoing rift-related volcanic activity and continuous magma upwelling. Seafloor spreading in the Afar is likely driven by the of gradual separation the Somalian and Arabian plates, resulting in active upwelling of magma and Oligo-Miocene lava flows that continuously create new oceanic crust away from the Mid-Ocean Ridge, thereby forming new seafloor along the East African Rift.

The observed magnetic anomalies were compared to the synthetic profiles of Girdler [14] and interpreted by the spreading model proposed by Laughton [15], which suggested seafloor spreading rate between 10 mm/yr and 19.6 mm/yr within the Western Gulf of Aden. The median valley, commonly observed along the Aden Ridge, is a central rift valley that forms due to tectonic activity and seafloor spreading (Fig. 10). It serves as the boundary between two opposing tectonic plates and is closely linked to the development of new oceanic crust. The median valley typically displays a distinctive topographic depression and is often characterized by volcanic activity.

The profile of track line 375 (Fig. 9; 10) that covers entirely the western part of the Gulf of Aden never exhibits submarine canyons but only the general depression at the central zone of the Aden ridges whose width is of the order of ≤100 km. Track line 375 exhibits excellent agreement in the characteristics of the anomalies when compared to the synthetic profile of Girdler [12]. This shows best fit spreading rates of the South (S) and North (N) limbs to be 1 cm/yr and 1.13 cm/yr respectively would likely be a magnetic anomaly profile. The bathymetric data depicts two bathymetry profiles labeled as AB and CD across the Aden Ridge, as shown in Fig. 3b and c (Fig. 3a). These bathymetry profiles reveal deeper median valleys (of 1.2 and 2.5 km, respectively), indicating reduced sediment accumulation in the region due to volcanic activities, which raise temperatures and consequently hinder the consolidation and preservation of organic materials essential for sedimentary basin formation. This disparity explains why there is a higher number of basins within the eastern Gulf of Aden compared to the western region. Presumably, the western region, still influenced by rifting processes, may experience slower rates of extension and basin formation. Additionally, the western Gulf of Aden experiences less pronounced tectonic activity and lower levels of volcanic involvement, leading to fewer basin developments.

Along profile track line 3502, magnetic variations are evident indicating presence of sedimentary infill in the smaller valleys observed near to the Gulf of Aden (i.e., 49 E°) which were approximately half the width of the median valley marked N in Fig. 11. These smaller valleys, typically depicts submarine canyons, that are formed through erosional processes, specifically from the action of turbidity currents originating from the uplifted mountains of the Aden Ridge on either side of the valley. During periods of reduced tectonic activity including seafloor spreading, submarine canyons can persist as relict features, indicating their formation during a previous phase of more active tectonic activity. This phenomenon leads to the accumulation of sediment in the canyons. Following this, a seafloor hiatus occurs, during which magnetic anomaly values miss for a certain period of time. In the study area, this hiatus might correspond to 10 Ma as proposed by Girdler [14]. After the hiatus, seafloor spreading resumed at an increased rate, resulting in the formation of a larger general depression in the central zone of the Aden Ridge hence large negative magnetic anomaly [15] marked M in Fig. 11. This large magnetic anomaly signifies an augmented supply of magma from the mantle and a higher level of volcanic activity in the region.

6. Conclusion

The study aimed to assess seafloor spreading rates and kinematics of the 3rd arm of the Afar triple junction. Results from this study show that seafloor spreading commenced at ca.16 Ma, with initial spreading rate of 15.547 mm/yr (Table 1, Fig. 4). The minimum and maximum sea floor spreading rates in the Afar region since its initiation at 16 Ma is 12.28 mm/yr at 6 Ma and 20.122 mm/yr at 13 Ma.

This seafloor spreading is attributed to the formation of the Gulf of Aden, resulting from the separation of the two sturdy plates (Arabian and Somalian plates) influenced by the active Afar hotspot. However, the western conjugate margins of the Gulf of Aden are obscured by young Oligo-Miocene lavas of the Afar mantle plume.

This study forms the basis for understanding seafloor spreading in the Afar region and enhances more understanding of the mechanisms driving tectonic plate movement. Also, the work examines the contribution of volcanic activity and sedimentation to the potential development of hydrocarbon resources in the study area. Such knowledge is crucial for resource exploration and development in the area.

Data availability

The data utilized in the manuscript can be accessed via the GEBCO database and https://www.earthbyte.org/category/resources/data-models/.

CRediT authorship contribution statement

Duke N. Nyangena: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Athanas S. Macheyeki:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Seetharamaiah Jagarlamudi:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Duke Nyarera Nyangena reports financial support was provided by The KFW bank. Athanas Macheyeki reports a relationship with The University of Dodoma that includes: non-financial support. Zahirovic Sabin has patent issued to Duke Nyarera Nyangena.

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