A Review of Earthquake Source Parameters in the Main Ethiopian Rift

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1. Introduction

The main Ethiopian rift (MER) is one of the most volcanically and seismically active regions in the East African Rift System (EARS). The region has different complex tectonic deformations located at the rift margins and floor (Figure 1). Structurally, the MER marks the two oceanic rifts: the Red Sea and the Gulf of Aden, which are propagating towards a triple-triple-triple junction in the Afar depression [1–4]. The Afar depression is supposed to be linked with the MER at a triple junction [5], where earthquakes are highly distributed (Figure 1), and complex geodynamic deformations reveal several rift structures. Within the MER, the localized magmatism may be extensional through dyking and intrusions [6, 7].

Focal mechanisms of earthquakes may describe a type of deformation and tectonic style. Thus, a clear tectonic style of the MER may provide basic information for defining
In this study, we collect earthquake source parameters computed using first-motion polarities and waveform inversion techniques to assess the seismic activity of the region. We have also computed the source parameters of two earthquakes using a time domain moment tensor inversion from waveform data. The solutions of worldwide earthquake source parameters are available from the Global Centroid Moment Tensor (CMT) catalog [8] and the United States Geological Survey (USGS) catalog, but solutions are available only for strong and moderate earthquakes at different time periods and magnitude thresholds. So far, the kinematics of the study region is mainly based on the focal mechanism of moderate earthquakes computed using first motions down to a lower threshold. Thus, we used source parameters of earthquakes of the MER and surrounding areas to improve the current tectonic knowledge concerning the geodynamic context.

The structurally damaging earthquake, like the Kara Kore earthquake with magnitude 6.4, destroyed the Majete town and was felt within the region [9]. From time to time, significant intermediate earthquakes repeatedly strike several sites in the region. Therefore, good knowledge about the MER current geodynamics is crucial. Recently, earthquakes due to tectonic and volcanic eruptions have attracted human beings. Earthquakes within the MER are historically documented by [9–17] at different times. However, seismic stations used for recording earthquakes in the region are not enough as needed in the past few years [14, 16]. Thus, earthquake source parameters were not properly compiled together, and the detailed study of earthquakes was mostly performed at the local level but poor at the regional level, which needs further investigation. Earthquake source parameters may provide information about the focal mechanisms of earthquakes used to determine fault parameters, and focal depths may give information about the source. Therefore, the current study is aimed at compiling earthquake source parameters that are computed using different techniques and at evaluating the current deformation and the role of magmatic intrusions and faulting in facilitating the seismicity of the MER.

2. Tectonic Setting

The MER is a key rift sector that connects the Red Sea and the Gulf of Aden in the Afar depression, where rifting follows the divergent boundaries of the Nubian, Somalian, and Arabian plates at different tectonic evolution stages [4, 5, 18, 19] (Figure 1). It marks the transition region from continental rifting to incipient seafloor spreading in the Afar depression. The MER is oblique to the end of the southern Red Sea and the Gulf of Aden [20]. Mostly, the MER forms the active plate boundaries of the Nubian and Somalian plates that run through
Focal mechanisms of the events were computed from P-waves compiled from [15] in the northern Ethiopian rift. Global and plate tectonic models approximated the rift spreading rate to 5±1 mm/yr and 6±1.5 mm/yr, respectively [24, 25].

The tectonic and dyke intrusions play a central role in facilitating the seismicity within the region [26–29]. In the MER, deformation is focused along 20 km wide, 60 km long magmatic segments [23]. However, strain accumulation is transferred from border faults to the magmatic segments along the rift floor [30]. Thus, an extension has migrated away from the bordering failure faults and has localized to rift-aligned magmatic segments at the rift floor [5]. The extension is accommodated through dyking and magmatic underplaying processes for crustal thinning within the region [7].

Crustal thickness beneath the northern and southern parts of the MER and the surrounding areas is not uniformly distributed. The seismogenic thickness might be correlated with the depth of the earthquakes. The elastic and seismogenic thicknesses increase within the MER from northward to southward [31]. For example, crustal thickness increases from 24 km to 38 km as we go from the southern Afar depression to the southern MER [32, 33]. Small- to moderate-magnitude earthquakes may occur at shallow depths in the different parts of the region. Accordingly, earthquakes with focal depths of 5–12 km have been reported in the MER and southern Afar [12, 14, 34]. However, within the region, focal depths down to the lower crust have also been reported.

3. Data and Method

In this work, we compiled focal depths and mechanisms of earthquakes from several published studies [11, 14, 15, 17, 35]. In addition, we used the International Seismological Centre (ISC) and United States Geological Survey (USGS) catalogs. Earthquake source parameters are shown in Table 1 while epicentral earthquake distribution compiled from the USGS catalog is shown in Figure 1. For the compiled results, many controversial solutions for earthquake focal depths are often the case.

We compiled the source parameters of two events from [11]. The source parameters of the six earthquakes that were computed from the moment tensor inversion for the August 2002 earthquake sequence in northern Afar and of the four events that were computed using waveform inversion in a time domain linear inversion algorithm [36, 37] by [14] have been compiled. The source parameters of the seven events that were computed using the full moment tensor inversion using the grid search algorithm of [38, 39] using the 1-D velocity model of [16] have been compiled from [35].

Furthermore, we have compiled the source parameters of earthquakes from several published works that were computed using first-motion polarities. Accordingly, 33 events were compiled from [15] in the northern Ethiopian rift. Focal mechanisms of the events were computed from P and SH wave polarities using the grid search algorithm of [40]. In the central MER, 21 events were compiled from [14]. Focal mechanisms of earthquakes were computed using first-motion polarities and amplitude ratios of FOCMEC [40]. In addition, epicentral locations of 4951 events were compiled from [35] (supporting material) as shown in Figure 2. Furthermore, we have compiled earthquake source parameters for larger magnitude earthquakes from the ISC catalog (Table 1), and the epicentral locations of earthquakes compiled from the USGS catalog for the period 1960 to 2019 are plotted in Figure 1.

In addition, three-component broadband waveform data are obtained from the Data Management Center of the Incorporated Research Institutions for Seismology (IRIS DMC) and used for moment tensor inversion. We used broadband data from a minimum of nine phases of seismic stations at epicentral distances in the range of 142–1275 km, successfully recording the 2017 and 2018 earthquakes with magnitudes Mw 5.0 and 5.1, respectively. We selected broadband seismic stations with a high signal-to-noise ratio, and all three-component broadband waveform data qualities were used.

In this study, we applied the moment tensor inversion that efficiently reduces the nonuniqueness of the polarity solutions and better characterizes the earthquake source parameters [41]. Here, we have critically examined the source parameters of two moderate earthquakes using the time domain moment tensor inversion. We used regional broadband data and the 1-D local velocity model of [42]. We applied the approach developed by [43]. Synthetic seismograms are generated and fitted with observed seismograms through bandpass filtering in the time domain range of 0.02–0.05 Hz. Our uncertainty was computed using an error misfit of the L2 norm, which is equal to sqrt((d – s) * s) for earthquakes with Mw 5.0 and 5.1, respectively. Accordingly, the corresponding source parameters are extracted and computed. Here, we used earthquake data from three-component broadband seismic stations, and the selected broadband waveform data are suitable for filtering in a wide range of frequency bands. Several authors have attempted moment tensor inversion from a single-station data, which is even sufficient to generate an accurate solution. However, we used a number of seismic stations and the quality of data in the inversion, which yielded good results [41, 44, 45]. Therefore, we are confident that the solution obtained in this study for source parameters of the event is robustly determined, and we take results as references for the source parameters of earthquakes compiled from different studies and catalogs; thus, the detailed study of earthquakes has been undertaken.

4. Results and Discussion

In this section, the earthquake source parameters compiled from several published works and international databases.
Table 1: Source parameters of earthquakes compiled from previously published works and the ISC catalog across the MER. The fault plane solutions are shown in Figures 2(a), 6, and 7, and the final column refers to the work in which the results are published: FJ98 [11], Ay6 [14], Ay7 [14], IK18 [35], and ISC catalog.

<table>
<thead>
<tr>
<th>Date</th>
<th>Origin time</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
<th>Rake (°)</th>
<th>Depth (km)</th>
<th>Magnitude</th>
<th>Reference</th>
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<td>189</td>
<td>41</td>
<td>-90</td>
<td>9</td>
<td>5.6</td>
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<td></td>
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<tr>
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<td>5.49</td>
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<td>41.08</td>
<td>9.89</td>
<td>126; 288</td>
<td>71; 20</td>
<td>-84; -107</td>
<td>7</td>
<td>4.4</td>
<td>Ay6</td>
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<td>9.94</td>
<td>86; 310</td>
<td>33; 65</td>
<td>-111; -51</td>
<td>5</td>
<td>4.3</td>
<td>Ay6</td>
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<td>45; 46</td>
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<td>7</td>
<td>4.2</td>
<td>Ay6</td>
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<tr>
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<td>9.91</td>
<td>103; 257</td>
<td>59; 33</td>
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<td>6</td>
<td>4.2</td>
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<td>13.5061</td>
<td>312; 146</td>
<td>56; 44</td>
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<td>5.0</td>
<td>Ay7</td>
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are briefly reviewed and related to the pertinent features of the MER. The epicentral locations are plotted in Figures 1 and 2(a), and the focal mechanisms of some events are shown in Table 1. The moment tensor inversion results computed in this study are also shown in Table 2. Accordingly, the magnitudes and focal depths of the two events are Mw 5.0 and 5.1 and 9.7 and 20.2 km for the 2017 and 2018 earthquakes, respectively. Our discussion is based on earthquake distribution, focal depth, and focal mechanism by comparing results obtained from different sources.
4.1. Earthquake Distribution. The earthquake distribution is mainly concentrated at the rift floor and rift margins, and very few earthquakes are at adjacent plateaus (see Figures 1 and 2(a)). The Afar depression, the Red Sea, and the Gulf of Aden are very active (Figure 1). In the Afar depression, the trend of earthquake distribution shows the east-west
elongation of the Gulf of Aden and the NW-SE and NNW-SSE elongations of the Red Sea towards the Afar triple junction (Figure 1). The earthquake distribution is highly concentrated at the rift floor of the Afar depression with sparsely distributed events in the MER (Figure 1). Outside of the rift floor, earthquakes are highly concentrated at the margins of the Afar depression and the northern Ethiopian plateau (Figures 1 and 2(a)). The N-S trending border faults could induce the earthquake distribution near the rift margins of the Ethiopian plateau and might be related to the opening of the Red Sea [5].

We observed that the majority of earthquakes are concentrated along 20 km wide, 60 km long magmatic segments of the rift floor. This indicates that strain accumulation is transferred from border faults to the magmatic segments along the rift floor, and an extension has migrated away from border faults and is localized to rift-aligned magmatic segments at the rift floor. We can conclude that deformation is most likely due to strain accumulation transferred from border faults to the magmatic segments along the rift floor through dyking and magmatism which is underplaying processes for crustal thinning within the region.

The elongations of earthquake clusters generally show a NE-SW trend in the MER, E-W in the Gulf of Aden, and NW-SE in northern Afar (Figure 1). The concentrated seismic activity at the margins of the Ethiopian plateau might have resulted from a high-stress concentration due to the lateral density contrast and differences in lithospheric thickness between the uplifted Ethiopian plateau and the Afar

**Figure 4:** Focal depth vs. latitude for earthquakes compiled from different sources as shown in Table 1. (a) Based on the first polarity readings of [15, 17], (b) from the ISC catalog, and (c) from waveform modeling by [11, 14, 35].
depression [32, 46]. The margin of the southeastern Ethiopian plateau is seismically not active except for small cluster earthquakes at the southern margin of the Gulf of Aden (see Figure 1). The margin of the central MER is also characterized by scattered earthquakes.

4.2. Hypocentral Distribution. The source parameters of intermediate magnitude earthquakes are determined from waveform modeling, while the first polarity reading is used for small-magnitude earthquakes in several studies in the MER. The plots of the spatial distribution for focal depths are shown in Figures 2(b), 3, and 4, while the plot of the magnitude versus focal depth is shown in Figure 5. The plots for fault plane solutions are shown in Figures 6 and 7.

In our discussion, we compare the hypocentral depths compiled from different sources shown in Figures 2(b), 3, and 4. The largest focal depth of ~50 km is observed, while most earthquakes have shallow depths within 0–30 km (Figure 2(b)). Hypocentral depth distribution has been plotted in Figure 3 for earthquakes compiled from the USGS catalog from 1960 to 2019. Accordingly, the largest focal depth of ~65 km has been observed, but few earthquakes are observed in the range of ~40–65 km. Generally, hypocentral depths range from the near surface to 35 km, and most of earthquakes clustered appear to be fixed at 10 km and 33 km (see the histogram of Figure 3(b)).

On the other hand, earthquake focal depths combined from different previous studies and ISC are shown in Table 1 and Figure 4. Focal mechanisms computed using the first polarity reading have a peak focal depth of ~20 km, while the majority of the earthquakes have focal depths between 3 and 14 km. Events are concentrated within 7–10°N (Figure 4(a)). The hypocentral depth peak of ~23 km is observed for earthquakes compiled from the ISC catalog, but the majority of earthquakes have focal depths of 10 to 12 km and are concentrated between 4° and 16°N (Figure 4(b)). Furthermore, the source parameters of events that are computed using moment tensor inversion have focal depths of 3–10 km (Figure 4(c)), which is consistent with a brittle-ductile transition zone in the region [14, 31, 42].

Earthquakes compiled from the supporting information of [35] and the USGS catalog for the period 1960 to 2019 have focal depths from the near surface to ~35 km (Figures 2(b) and 3(a)). In general, most events are within the upper crust, which might be due to the stress from nearby faults and dike intrusion in the brittle seismogenic zone of the region at shallow depths. The crust thickness thins dramatically from ~26 to 20 km in Afar [47], whereas it is ~15 km beneath the Danakil depression, suggesting ongoing crustal thinning and magma intrusion [46–48] at shallow depths beneath the region. Thus, relatively deeper earthquakes beneath the region with a focal depth of ~35 km and above may suggest upper mantle earthquakes (Figures 2(b) and 3(a)). However, focal depths of earthquakes as deep as in the upper mantle reported in the compiled international database are not consistent with previously published works in the region which may be due to routine processing problems in the international databases.

Generally, focal depths of different studies show uncommon agreement with each other, and routine processing problems in the international databases should be investigated. Furthermore, the discussion confirmed tectonic and dike intrusions in the brittle seismogenic zone of the region due to ongoing crustal thinning and magma intrusion. There is certainly a problem of large uncertainty in depths reported in international catalogs, especially in the early period.
Larger earthquake magnitude values of 3.5 to 6.0 (Figure 5(a)) and of 5.5 to 6.5 (Figure 5(b)) are observed with focal depths of 0 to 20 km. The results may suggest and illustrate that relatively larger earthquakes are found to be within the upper crust of the elastic lithospheric thickness of the region.

4.3. Earthquake Focal Mechanism and Its Implications. The fault plane solutions are combined from [11, 14, 15, 17, 35] (ISC) which are computed using moment tensor inversion and polarity readings. The combined fault plane solutions are listed in Table 1 and Figures 2(a), 6, and 7. The focal mechanisms show the existence of normal faulting along the margins of the Ethiopian and Somalian plateaus (Figures 6 and 7). Within the MER and Afar depression, normal faults and strike-slip components are observed (Figures 6 and 7).

Predominantly normal faulting or normal faulting with small strike-slip components is observed in the region, which is in agreement with the previous works of [11, 13, 15]. Fault plane solutions with dominant normal faults and significant strike-slip have been observed at the northern MER and northern Afar with NE-SW and NW-SE trends, respectively. The strike-slip component is also suggested from the previous works of [49, 50]. Only a normal focal mechanism is found in the southern part of MER with an NNE-SSW trend (Figures 2(a), 6, and 7). The interpretation of the focal mechanism might be related to the trend of the MER and the geological observations [51–53] found within the region. Fault plane solutions of some events found in Afar show E-W, N-S, and NNW-SSE trends with roughly north-south and east-west extensions.

In the Afar and Gulf of Aden and at the margin of the Somalia plateau, fault plane solutions of earthquakes may suggest the separation of Arabia from Africa with a north-south extension that is consistent with many focal mechanisms in the central Afar at the triple junction where Arabian plate is now drifting away from Africa plate (Figures 1, 6, and 7). The southern Afar focal mechanisms may show that the region is at the transition zone between the north-south striking southern Red Sea rift fault and the NE trending MER [54]. The strike-slip components

Figure 6: Fault plane solutions of earthquakes in the MER and Afar. Red beach balls represent earthquakes computed from polarity readings from [15, 17], and black beach balls represent earthquakes compiled from the ISC catalog.
observed in the northern Afar might be related to the counterclockwise rotation of the Danakil microplate [25, 55], and the mechanisms would indicate an oblique-slip deformation between the Nubian plate and the Danakil microplate.

The seismically active region of the northern Ethiopian plateau/rift margins (Figures 1 and 2(a)) could have normal focal mechanisms with the NNW-SSW trend (Figures 4 and 6) that could be caused by the north-south trending border faults related to the opening of the Red Sea [5]. Generally, focal mechanisms along the northwestern border of Afar are predominantly showing an east-west extension. The focal mechanism along the eastern border of Afar (the margin of the Somalian plateau) shows an east-west trend with a north-south extension, which might be consistent with the Arabian plateau movement towards the north and the Arabian plateau towards the south, respectively (Figures 6 and 7). Therefore, the north-south extension in the northern part of the region could be related to the Nubian-Arabian plate motion.

Focal mechanisms along the northern and central parts of the MER are mostly normal in style, congruent to the extensional orientation in the rift roughly E-W, while some strike-slip components (Figures 6 and 7) are likely associated with the reactivation of structures found in the region. Only normal faulting with a slightly east-west extension is observed in the southern part of the main Ethiopian rift. The absence of a strike-slip component may suggest that this particular region is neither associated with the microplate rotation (there is no microplate) nor associated with the reactivation of geologic structures.

4.4. Moment Tensor Inversion in the Time Domain. We computed the moment tensor inversion for the 2017 and 2018 earthquakes with magnitudes Mw 5.0 and 5.1, respectively. The moment tensor inversion results are shown in Table 2. Reliable source parameters have been selected for the best fit between observed and synthetic seismograms (Figures 8 and 9). The well-constrained hypocentral depths of the event
are estimated to be 9.7 km and 20.2 km for the 2017 and 2018 earthquakes, respectively. The focal depth at 9.7 km is within the upper crust, which might be due to stress from nearby faults and the dike intrusion in the brittle seismogenic zone of the region at a shallow depth beneath the MER, which is consistent with several compiled data. The focal depth at 20.2 km is found near the lower crust within the thinned crust. The lower crust of this particular event might be correlated to a tectonic earthquake that facilitated the deformation of the elastic seismogenic zone of the region due to strain accumulation at the border faults. This indicates the ongoing crustal thinning at the margin of the rift and plateau.

The focal mechanism obtained from the moment tensor inversion for the Mw 5.0 event indicates dominant normal faulting with a significant strike-slip component consistent with the extension of the Ethiopian plateau from the Somali plateau.

On the other hand, the focal mechanism obtained from the moment tensor inversion for the Mw 5.1 event indicates dominant normal faulting accompanied by a minor strike component at the western margin of Afar. The focal mechanism could have a roughly N-S trending (Figure 7) and could be induced by the north-south trending border faults related to the Red Sea opening [5].

The summary of results from Figures 6 and 7 shows that purely normal faulting and normal faulting with strike-slip components are observed in the MER and Afar depression. The region is dominated by normal faulting due to extensions in the region. On the other hand, the focal mechanism with the strike-slip component observed in the region may suggest the anticlockwise rotation of the Danakil microplate relative to the Nubian plate [25, 55], while some strike-slip components may suggest the reactivation of geologic structures in the region. From our seismicity distribution and focal mechanisms, the Red Sea and Gulf of Aden rifts

Figure 8: Moment tensor inversion in the time domain for the 2017 earthquake with the magnitude Mw 5.0 that was computed in this study. The panel is dedicated to waveform comparison (red color is used for data and black for synthetics). Stations are sorted based on epicentral distances, with station name, distance, azimuth, and maximal amplitudes on the left side. Up, RadAway, and TraRight of each station are written above the fits of observed and synthetic seismograms.
propagate towards the Afar depression. It is impossible to suggest that the Gulf of Aden is seismically more active than the Red Sea because the two regions are found to be very active (see Figure 1).

From the seismicity distribution and trends of focal mechanisms in the MER and Afar, the geodynamic implications of the region may suggest the separation of the Arabian plate from the African plate in large and the ongoing separation of the Nubian plate from the Somalian plate. In addition, the strike-slip components of the focal mechanism in the region may control the tectonic settings related to the microplate rotation and reactivation of local lineaments. Within the region, earthquakes may be induced by the stress at the rift margins and intrusions in the rift floor. From the hypocentral depth range, deformation throughout the region has been characterized by widespread lithospheric deformations due to inhomogeneous extensions.

5. Conclusions

In this study, we evaluated earthquake source parameters compiled from previous studies and international databases. Furthermore, the moment tensor inversion is performed from broadband seismic data for two earthquakes with magnitudes Mw 5.0 and 5.1 that occurred in the region in 2017 and 2018, respectively. For source parameters of earthquakes compiled from previous studies and obtained from the moment tensor inversion of this study, hypocentral depths of earthquakes are observed in the upper and lower crust ranges. Results from the waveform inversion show that earthquakes are almost from the upper crust, which are consistent with the previous studies. However, hypocentral depths of earthquakes compiled from the international databases are in the range of the crust to the uppermost mantle. The database routine-processing difficulty could result in hypocentral depths reaching the upper mantle. In general, the observed focal depth may suggest broad deformation throughout the upper and lower crusts, implying that magmatic intrusions and faulting are important in promoting seismicity throughout the main Ethiopian rift.

Fault plane solutions revealed normal faulting and strike-slip deformation mechanisms. The northern part of the region is tectonically very complicated, having normal faults with different trends and strike-slip components with...
different orientations. This implies that the region is undergoing enormous extensions between the three primary plates of the Arabian, Nubian, and Somalian plates, as well as the propagation of the Red Sea, Gulf of Aden, and MER towards the Afar region. Fault plane solutions positioned along the N-S edges of the Ethiopian plateau could be associated with the Red Sea's E-W opening towards the MER. The divergence between the Arabian and Somali plates may be revealed through focal mechanisms with E-W trends. The dominantly normal faulting with a significant strike-slip component of the focal mechanism in the central part of MER obtained from the moment tensor inversion has confirmed the extension of the Ethiopian plateau from the Somali plateau and the striking direction of the MER along the NE-SW. The southern part of the MER fault plane solution indicates the NNE-SSW trend with a roughly E-W extension direction of the rift. The distribution of earthquakes and the trends of focal mechanisms in northern Afar clearly demonstrate the propagation of the Red Sea and the Gulf of Aden towards Afar.

In general, the observed normal faulting mechanisms are consistent with the divergence of the major plates, whereas the observed strike-slip components in the region could be associated with the anticlockwise rotation of the Danakil microplate, and the mechanism would indicate an oblique-slip deformation between the Nubian plate and the Danakil microplate.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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