

Earthquakes Occurrence on the East African Coast and Their Implication on Stress Drop along the Davie Ridge of the East African Rift System (EARS)

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Abstract The Davie Ridge (also known as Davie fracture zone), considered as the seaward extension of eastern branch (Kenya Rift Valley) of the East African Rift System [1,2], is a 2200 km-long prominent relic fracture zone that cuts across the West Somali Basin [3-5]. It ranges between 30 and 120 km wide, with a west-facing scarp along the lower half of its length [2,6]. Earthquakes as deep as 40 km have been recorded below the Davie Ridge. However, recent seismic data shows that M_w 4.0 -5.0 earthquakes at crustal depths ($10 \leq d \leq 30$ km) are common. Since early 2018-2019, the Davie ridge has been characterized by high frequency of $4.4 \leq M_w \leq 5.4$ earthquakes occurrence. The purpose of the present research is to evaluate the stress drop along the Davie ridge using an empirical exponential relationship developed for M_w and fault parameters (length, width and rupture area) for the East African region and compare the results to those obtained from conventional body wave inversion. The results of this study show that, using empirical exponential relation, the stress drop, $\Delta\sigma$, and the corresponding fault (rupture) area, S^2 , ranges between 0.49-0.78 MPa and 15.7-32.5 km² respectively. Fault rupture area and stress drop results based on body wave inversion and empirical exponential equations for $M_w < 6.0$ are very similar. For $M_w \geq 6.0$, however, the fault rupture area is under-estimated and this tends to over-estimate the stress drop. Empirical exponential relations offer a rapid estimate

of fault parameters and stress drop for $M_w \leq 6.0$ earthquakes.

Keywords Earthquakes, Davie Ridge, Empirical Exponential Relation, Fault Parameters, Stress Drop

1. Introduction

The Davie Ridge, also known as Davie Fracture Zone, has been considered as the seaward extension of eastern branch (Kenya Rift Valley) of the East African Rift System (EARS) [1,2]. The Davie ridge is a 2200 km-long prominent relic fracture zone (Figure 1) cutting across the West Somali Basin [3-5].

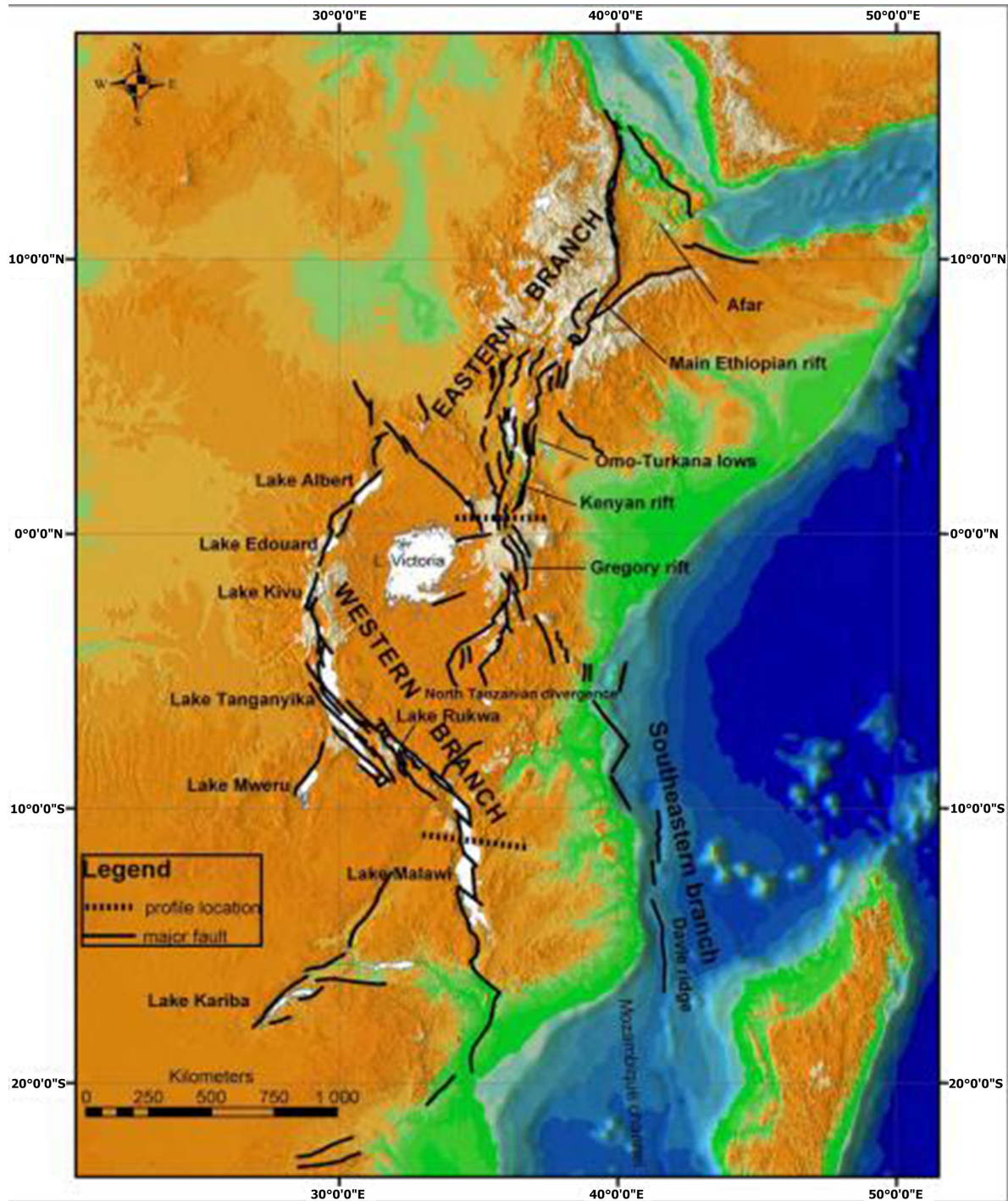


Figure 1. Seaward extension of the Eastern branch (Kenya Rift Valley) of the East African Rift system. After [1]

It ranges between 30 and 120 km wide, with a west-facing scarp along the lower half of its length, that rises as much as 2300 meters above the sea floor [2,6].

Earthquakes as deep as 40 km have been recorded along the Davie Ridge with the largest earthquake sequence (mb upto 6.4 and M_0 upto $5.0E18$) occurring during May and June 1985 off the coast of Tanzania-Mozambique border [5]. Evaluation of recent seismic data for the purpose of this study however shows that M_w 4.0-5.0 earthquakes at relatively shallow depths of 10 - 20 km are a common

occurrence along the Davie Ridge and Mozambique channel. The earthquake focal mechanism indicates that the Davie ridge is characterized by normal faulting with occasional oblique slip faulting. Seismic reflection, gravity and magnetic data from offshore East Africa allow the Davie Ridge (Fracture Zone) to be traced from 11°S to its intersection with the Kenyan coast at 2°S (Figure 2), constraining the relative motion of Madagascar and Africa [4]. Faults and fractures, probably associated with the Davie ridge (Fracture zone), have been mapped using

gravity and magnetic data between latitudes 2°21'S and 3°03'S and longitudes 40°08'E and 40°45'E by [7].

2. Materials and Methods

2.1. Review of Seismicity and Seismic Hazards

The eastern branch of the East African Rift System (EARS), the Kenya rift valley, and the Davie ridge are characterized by moderate level of seismicity. Small magnitude ($M \leq 3$) earthquakes described by [9] as earthquake swarms are common in eastern branch (Kenya rift) of EARS. In comparison to EARS, the Kenya rift shows a low seismicity. Major earthquakes in Kenya include the 1928 M_s 6.9 in central Kenya rift valley, an aftershock M_s 6.0, as well as the 1913 M_s 6.0 Turkana region earthquake [10,11].

Mulwa et al., [12] have assessed tsunami hazard potential on the East African coast due to earthquake occurrence along the Davie ridge using three earthquake scenarios of M_w 7.2, 8.0 and 9.0 and fault parameters (rupture length, width, and surface displacement/fault dislocation) derived from [13]. Table 1 summarizes fault parameters as well as the associated sea floor displacement and tsunami wave heights for the three earthquake scenarios.

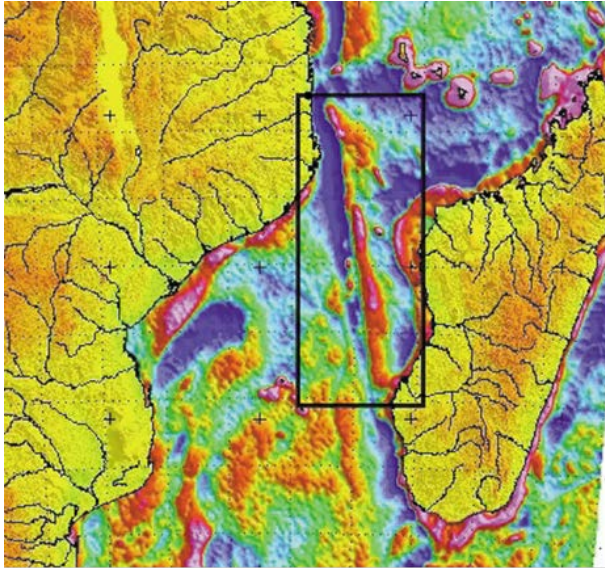


Figure 2. Satellite derived free-air gravity anomaly of the Davie Ridge/Fracture Zone enclosed in box (After [8])

Table 1. Fault parameters and associated sea floor displacement (m) and tsunami wave height (m) due to three earthquake scenarios along the Davie Ridge (After [12]).

M(M_w)	Strike*	Dip*(West)	Slip (m)	Length (km)	Width (km)	Sea floor displacement (m)	Maximum tsunami wave height (m)
7.2	0°	70°	3.5	60	35	≤ 0.5	1.0
8.0	0°	70°	7.6	200	50	≤ 3.0	5.0
9.0	0°	70°	20.0	1200	200	≤10.0	10.0

*Values of strike and dip are adapted from continental studies of the Kenya rift valley e.g. [19,20]

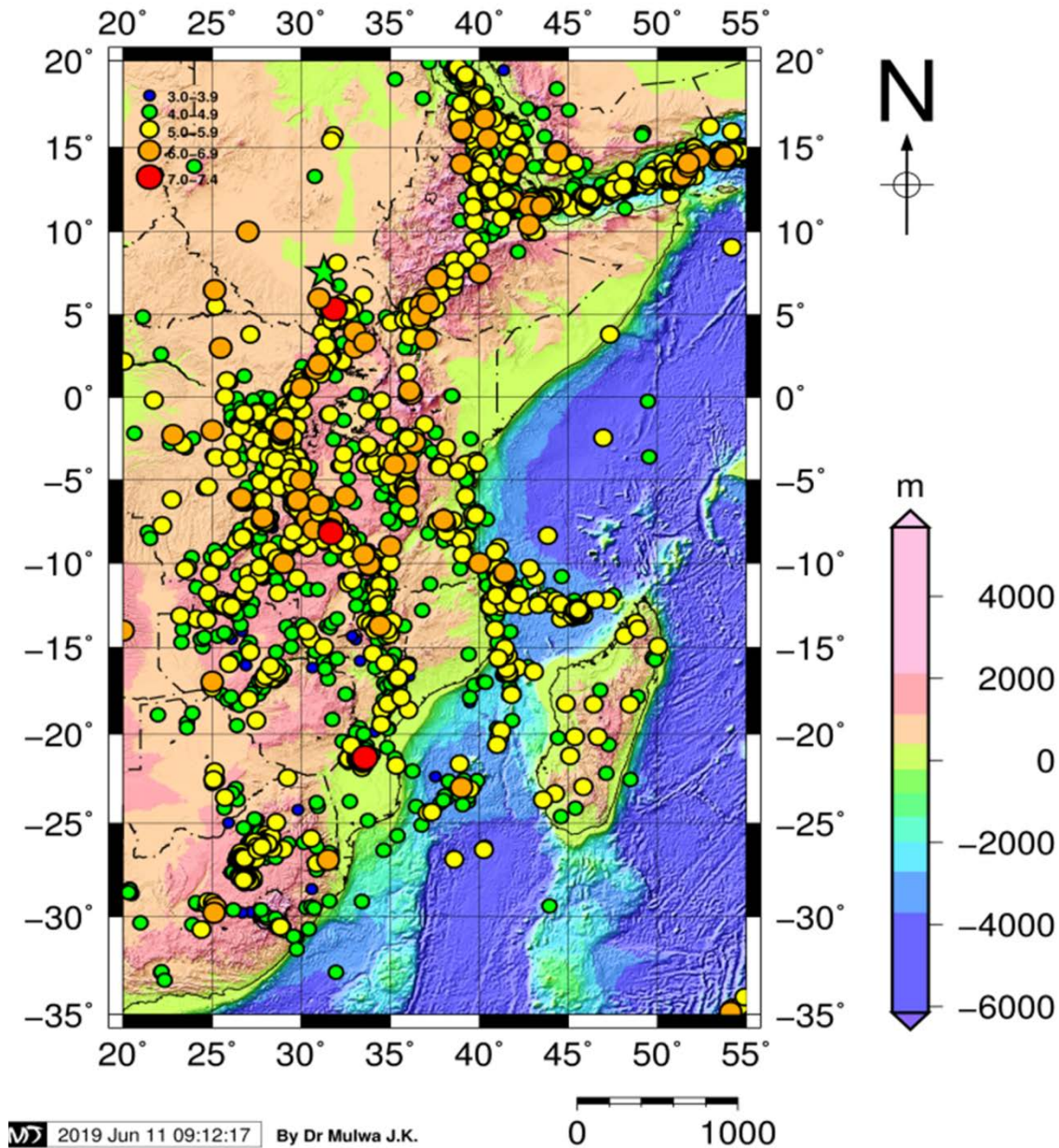


Figure 3. Distribution of earthquake epicenters on the eastern part of Africa from 1900 – May 2019 for ($M_w \geq 3.5$).

2.2. Earthquake Data

Subscription of the International Data Centre (IDC) SEL1 and REB products as well as supplementary earthquake data from International Seismological agencies/sources e.g. ISC, GFZ, USGS, NEIC e.t.c. has allowed continuous monitoring of earthquakes occurrence along the Davie ridge. For a period from 2018 to 2019, the Davie ridge has been characterized by high frequency of earthquakes occurrence. Figures 3 and 4 show the distribution earthquake epicenters on the eastern part of Africa including the Davie Ridge and the Mozambique channel from 1900-May 2019, and for the period January 2018 to May 2019 for $M_w \geq 3.5$, respectively.

In order to assess the stress drop along the Davie Ridge,

moment magnitudes (M_w) from the various seismological agencies, in addition to fault parameters by [13] have been used. Seismic moment M_0 (Nm) required for stress drop computation was calculated from the standard relationship between moment magnitude and seismic moment [14,15]. The fault rupture area, which is required for stress drop computation, for the respective moment magnitudes of earthquakes along the Davie ridge was determined from [13] using an empirical exponential relationship between fault parameters (fault length, width and rupture area) versus magnitude. These fault parameters have previously been determined based on empirical relationships, regression curves and coefficients as discussed by [13,16,17]. Figure 5 shows a plot of fault rupture area versus moment magnitude along the Davie ridge and the

empirical exponential relationship used in this study.

The stress drop along the Davie ridge was then computed based on the equation below by [18].

$$\Delta\sigma = 2.5M_o / S^{1.5} \quad (1)$$

where $\Delta\sigma$ is the stress drop, M_o is the seismic moment and S is the fault rupture area associated to a particular moment magnitude. Table 2 shows the moment magnitudes and the associated fault rupture area and stress drop along the Davie ridge.

Table 2. Moment magnitudes and the associated fault rupture area and stress drop calculated during this study

Moment magnitude (Mw)	Fault rupture area (km ²)	Stress drop (Mpa)
4.7	15.7	0.49
4.9	23.4	0.63
5.1	32.5	0.78
6.0	143.9	2.03
6.5	313.3	3.34
7.0	673.2	5.44
7.2	933.7	6.70

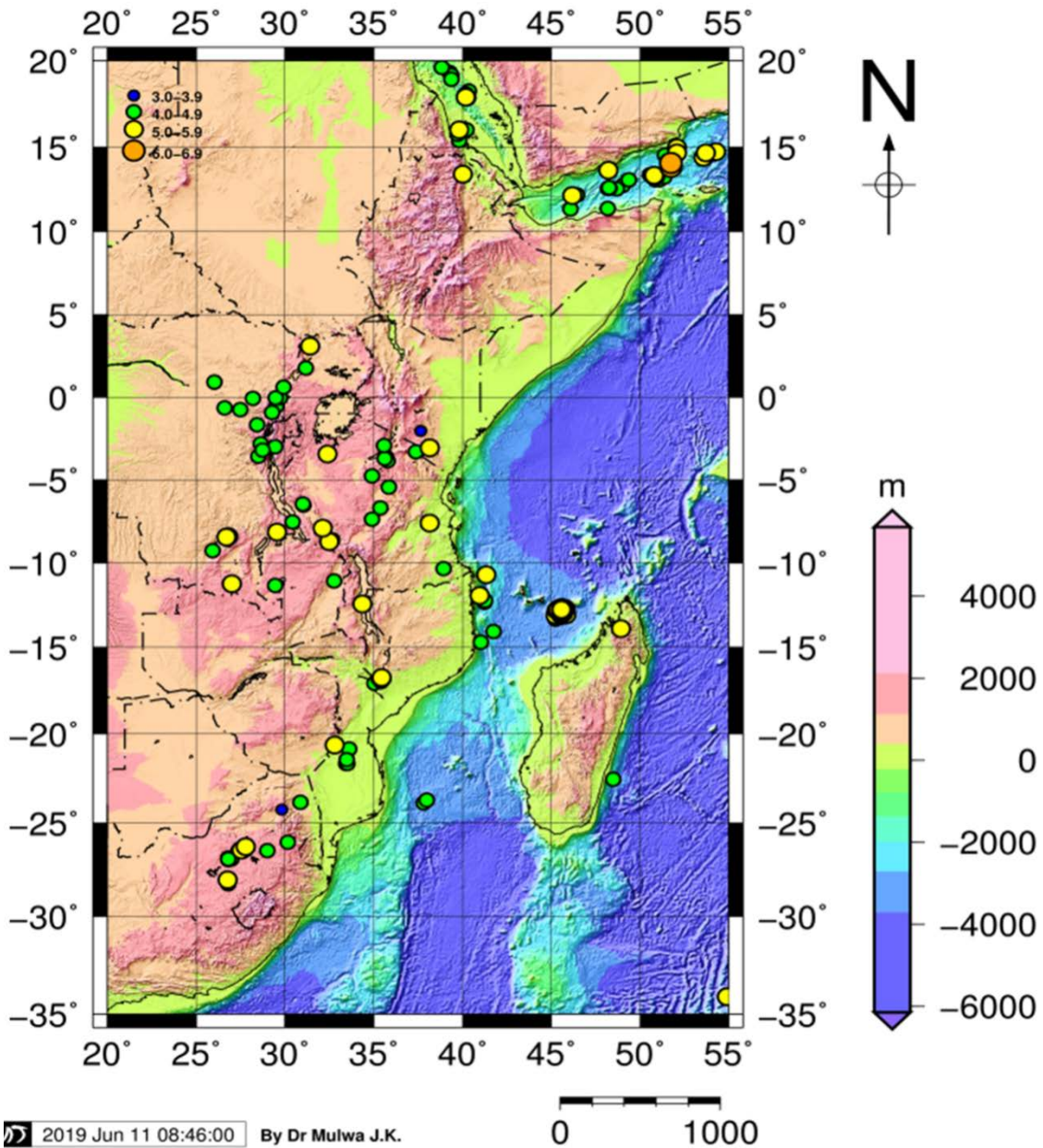


Figure 4. Distribution of earthquake epicenters on the eastern part of Africa for the period 2018-May 2019 (Mw ≥ 3.5)

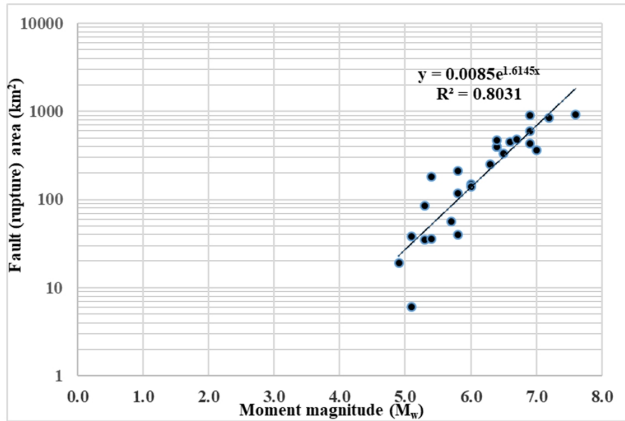


Figure 5. Fault rupture area (km^2) versus moment magnitude (M_w) along the Davie ridge

3. Results

The distribution of earthquake epicenters in Figure 4 shows that, out of a total of 364 events during the period from 2018 to May 2019, 222 events (61%) have occurred along the Davie Ridge (7) and Northwest of Madagascar (215). The magnitude (M_w) ranges between 4.4-5.4 and 4.4-5.9 respectively. Along the Davie Ridge, the estimated fault (rupture) area ranges between 15.7-32.5 km^2 for the lower and higher bound magnitudes respectively, and the corresponding stress drop ranges between 0.49-0.78 MPa.

4. Discussion

Empirical relationships, regression curves and coefficients under-estimate the fault rupture area and subsequently over-estimate the stress drop for magnitudes above a certain limit. The results from this study have been compared with previous works e.g. Mulwa [21], Mulwa and Kimata [22], [23,24] among others, who have used teleseismic body wave inversion to retrieve seismic moment and fault parameters and subsequently used these to compute the associated stress drop.

For teleseismic body wave inversion of the May 20, 1990 M_w 7.2 South Sudan earthquake, Mulwa [21] and Mulwa and Kimata [22] obtained seismic moment and fault rupture area of $7.65\text{E}+19$ Nm and 2400 km^2 respectively. The calculated stress drop due to the May 20, 1990 South Sudan earthquake was 1.63 MPa. Using the empirical exponential relationship obtained in the present study, the calculated fault rupture area and stress drop are respectively 933.7 km^2 and 6.70 MPa. This overly under-estimates the rupture area but over-estimates the stress drop by about 5.1 MPa.

Results of seismic body wave inversion of the October 12, 1992 M_w 5.8 Cairo earthquake by [23], however, show that the fault rupture area and stress drop are somewhat quite similar to those obtained using empirical exponential

relation apart from slight over-estimate of rupture area and under-estimate of stress drop using the latter method. [23] obtained values of 99 km^2 and 1.85 MPa from body wave inversion. The results using the empirical exponential relation are, however, 105.5 km^2 and 1.66 MPa respectively. These results do not differ significantly from those using seismic body wave inversion.

Reference [24] inverted P and SH body waves to determine the source processes of the 1994 M_w 6.6 earthquake and its aftershocks. The inversion results show that the fault rupture area is approximately 600 km^2 and the seismic moment is $1.1\text{E}+19$ Nm. Using these values, the calculated stress drop is 1.87 MPa. From the empirical exponential relation, however, the rupture area is 377.1 km^2 and the associated stress drop is 3.76 MPa.

The August 3, 1993 and November 22, 1995 (M_s 7.2) earthquakes occurred in the Dead Sea fault system (DSFS) with the 1995 event originating in the vicinity of the 1993 event and propagating northwards where seismic moment releases ($M_o = 7.4\text{E}18$ and $38\text{E}18$) due to two sub-events took place [25]. Inversion results of teleseismic body waves for the 1995 event show that the stress drops due to the two sub-events are 1.2 MPa and 2.0 MPa respectively. Empirical exponential relation however gives stress drops of 3.34 MPa and 5.44 MPa respectively. These values of stress drops obtained using the empirical exponential relation are as well slightly overestimated due to probably an under-estimation of the fault rupture area. For the 1993 earthquake, however, seismic moment release of $1.4\text{E}18$ equivalent to M_w 6.0, the stress drops from seismic body wave inversion and empirical exponential relation are 3.5 MPa and 2.03 MPa respectively. As the earthquake magnitude for this event is very close to that of [23], the stress drops obtained from teleseismic body wave inversion and empirical exponential relation do not significantly differ. This would support the fact that fault rupture area and stress drop for $M_w < 6.0$ obtained using the empirical exponential relations and waveform inversion are very close.

5. Conclusions

Earthquake magnitudes have a strong bearing on the fault parameters and stress drop. The results obtained from this study show that fault rupture area and stress drop results obtained from body wave inversion and empirical exponential equations for earthquake magnitudes of $M_w \leq 6.0$ are very similar.

Conversely, stress drop obtained based on fault parameters using empirical exponential relationships, regression curves and coefficients e.g. [13,16,17] and Mulwa (this article) are overestimated for $M_w > 6.0$. For such $M_w > 6.0$, the fault rupture area is overly under-estimated and this tends to over-estimate the stress drop.

Nevertheless, the empirical exponential relationships, equations, curves and coefficients offer a rapid estimate of fault parameters and stress drop.

This paper recommends teleseismic body-wave inversion/waveform modeling method e.g. [18,21-29] e.t.c to retrieve source (fault) parameters, seismic moment and use these for computation of the associated stress drop especially for $M_w > 6.0$.

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