Tectonic Structures Across the Eastern African Rift Likely to Pose the Greatest Earthquake Hazard in Kenya

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Keywords: Tectonic structures, Teleseismic, body-wave inversion, Seismotectonics

ABSTRACT

Earthquakes in Kenya are likely to be concentrated along the Kenya Rift Valley due to the slow divergent movement of the rift and hydrothermal processes within the geothermal fields. This implies slow but continuous radiation of seismic energy which relieves stress in the subsurface rocks. It is therefore unlikely that the Kenya rift poses significant earthquake hazard in Kenya.

On the contrary, the NW-SE trending rift/shear zones such as the Aswa-Nyangia fault zone and the Muglad-Anza-Lamu rift zone are more likely sites of major earthquakes in Kenya and the East African region. These rift zones have been the sites of a number of strong earthquakes in the past such as the $M_w = 7.2$ southern Sudan earthquake of May 20, 1990 and aftershocks of $M_w = 6.5$ and 7.1 on May 24, 1990; the 1937 Ms = 6.1 earthquake north of Lake Turkana close to Kenya-Ethiopian border, and the 1913 $M_s = 6.0$ Turkana earthquake, among others.

We have attempted to determine the source parameters of the May 20, 1990 southern Sudan earthquake by inversion of teleseismic body-waves, and the implications of this earthquake on the seismotectonics of southern Sudan, as well as the central and southern parts of Kenya. The results of teleseismic body-waves inversion show that the best solution for the May 20, 1990 southern Sudan earthquake consists of only one event on a fault having strike, dip and rake of $315^o/84^o/-3^o$. The fault plane is characterized by left-lateral strike slip fault mechanism. The focal depth for this earthquake is 12.1 km, seismic moment $M_o = 7.65 \times 10^{19}$ Nm and moment magnitude, $M_w = 7.12$ ($\cong 7.2$). The fault rupture started 15 seconds earlier and lasted for a duration of 17 seconds along a fault plane having dimensions of length $\cong 60$ km and width $\cong 40$ km. The average dislocation along the fault is 1.1 m and the stress drop, $\Delta\sigma$, due to this earthquake is 1.63 Mpa.

The distribution of historical earthquakes from southern Sudan through central Kenya generally shows a NW-SE alignment of epicenters. On a local scale in Kenya, the NW-SE alignment of epicenters is characterized by earthquakes of local magnitude $M_l \leq 4.0$, except the 1928 Subukia earthquake ($M_s = 6.9$) in central Kenya. This NW-SE alignment of epicenters is consistent with the trend of Aswa-Nyangia fault zone, from southern Sudan through central Kenya and further southwards into the Indian Ocean. These zones of strong earthquakes are the likely to pose the greatest earthquake hazard in the region.

1. INTRODUCTION

Tectonic structures exist across Eastern Africa (Figure 1). These zones are potential areas for earthquakes which can pose a threat and subsequent challenge to attaining economic development in order to attain Vision 2030. In view of this, we try to investigate if the tectonic structures pose any serious potential earthquake hazard in Kenya and adjacent countries.

The geology, tectonics and volcanism in Kenya since the Tertiary are discussed elsewhere and readers are referred to Baker (1986, 1987), Baker and Wohlenberg, (1971), Baker et al. (1972, 1988), Logatchev et al. (1972), King and Chapman (1972), Smith (1994), Smith and Mosley (1993), Chorowicz (2005), Atmaoui and Hollnack (2003), Braile et al. (1995), Gregory (1921), Sikes (1926), Saggerson (1991), and Schluter (1997) among others, for comprehensive discussions.

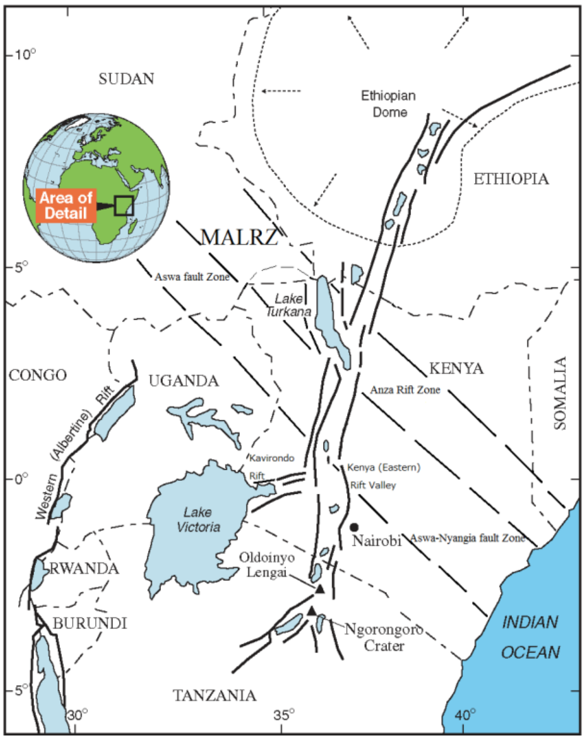

Figure 46: Location map of Kenya showing outlines of the Kenya Rift Valley and the NW-SE trending rifts/shear zones.

2. SEISMICITY

The East African region is characterized by a moderate level of seismicity which is mainly controlled by the structural trend of the East African rift system (Figure 2). Usually small magnitude earthquakes are common on the eastern branch (Kenya rift) of East African Rift System (EARS) and these have been described as earthquake swarms by Ibs-von Seht et al. (2008), who have also further given an overview of the occurrence of earthquake swarms in the Kenya rift. In comparison to the whole of the EARS, the Kenya rift shows a relatively low seismic activity. Except for M_s=6.9 earthquake in 1928 in the central part of Kenya rift, no M>5 earthquakes in the Kenya rift have been reported since 1928. Numerous local earthquake studies by Rykounov et al. (1972), Pointing et al. (1985), Maguire et al. (1986, 1988), Young et al. (1991), Tongue et al. (1992, 1994) and Tongue (1992) have established a high microearthquake activity in the Kenya rift.

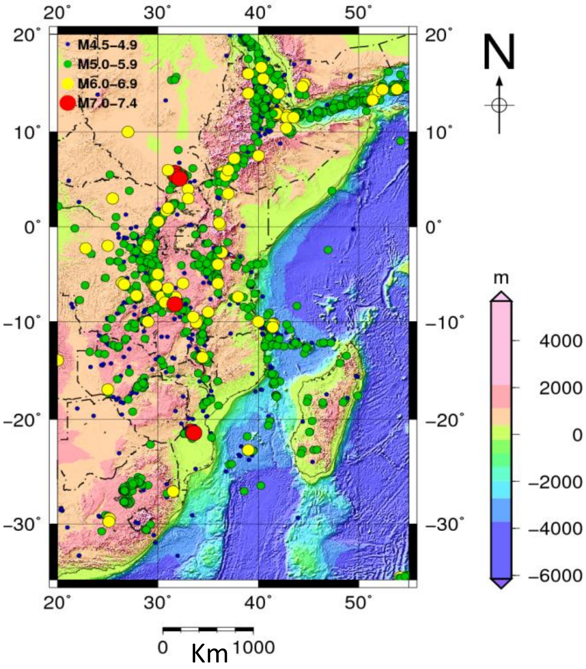

Figure 2: Seismicity in the eastern part of Africa between 1900-2012 for Mw≥4.5

Ibs-von Seht et al. (2001) reported a constant rate of ~10 M<3 earthquakes per day for the southernmost part of the Kenya rift. The background seismicity of the Kenya rift in this southern part was restricted to depths of 10 km whereas the earthquake swarms were generally shallow with most of the hypocenters between 0 and 6 km deep. For the central Kenya rift, Young et al. (1991) reported more than 500 M<2.7 earthquakes during a three months period in Lake Bogoria region. Tongue et al. (1994) observed a short (lasting less than one day) M<2 earthquake swarm in Lake Baringo region. The swarm earthquakes were found to form a narrow, elongated cluster in the center of the rift at ~5 km depth. Young et al. (1991) and Tongue et al. (1994) attributed the earthquake swarm activity to emplacement of dikes.

A review of the seismicity in Kenya from 1906-2010 (Figure 3) undertaken for the purpose of this study shows that the entire N-S trending rift system, including the E-W trending Nyanza (Kavirondo) rift are characterized by a high rate of seismicity.

Even though the occurrence of large earthquakes in the East African region is rather low, historical records based on macroseismic information, supplemented by re-examination of instrumental reports to re-evaluate the position and size of major earthquakes, as well as recent deployments of seismic monitoring networks by United States Geological Survey (USGS) and International Monitoring System (IMS) show a somewhat increase in the seismic activity in the region as shown in Figures 2 and 3. Figure 2 shows that the eastern part of the African continent has in the past experienced strong (M_w≥ 6.0) earthquakes between the period 1900-2012.

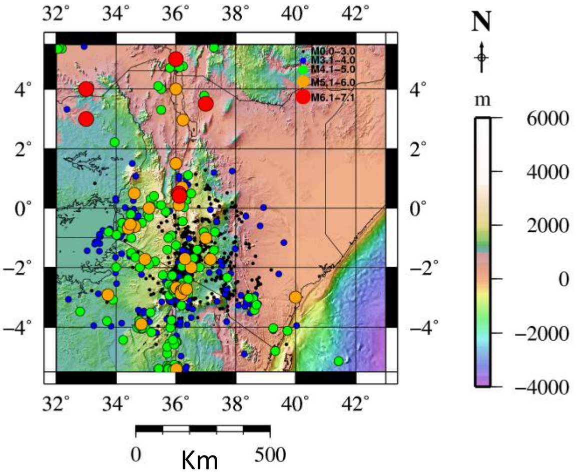

Figure 3: Seismicity in Kenya for the period 1906-2010.

Earthquake records for the period 1900-1930 have been obtained from published microseismic information while those for the period 1973-2010 have been obtained from various international catalogues, e.g., National Earthquake Information Center (NEIC) and Centroid Moment Tensor (CMT) catalogues. Consequently a significant lack of information on earthquakes exists for the period 1931-1972. Other significant earthquakes documented by Midzi et al. (1999) but lacking epicentral information and therefore not plotted in Figure 2 are tabulated in Table 1.

Table 1: Other significant earthquakes in the eastern African continent (After Midzi et al. 1999)

Year	Magnitude (M_s)	Area/Country
1945	6.0	Masaka/Uganda
1960	6.1	Awasa/Ethiopia
1961	———	Kara Kore/Ethiopia
1966	6.1	Tooro/Uganda
1969	6.3	Serdo/Ethiopia

The earthquake considered for the purpose of this study is the May 20, 1990 event which occurred in southern Sudan (Figure 4). The epicenter of this earthquake is located at the northern extremity of the western branch of the East African rift system within NW-SE trending Aswa rift zone in southern Sudan. This region has been considered as a triple junction between the western branch of EARS, and the Aswa rift zone which continues southeastwards into Kenya as Aswa-Nyangia fault zone, a diffuse, poorly defined intra-continental transform fault zone linking the western and eastern branches of EARS (Chorowicz and Mukonki, 1979; Kazmin, 1980). The earthquake is of significance since it is the strongest earthquake, in terms of magnitude, to occur in the eastern Africa region during the 20th Century. It caused damage in southern Sudan as well as severe shaking in parts of Uganda and Kenya, and was accompanied by aftershocks on May 24, 1990 of moment magnitudes M_w = 6.5 and 7.1 (Figure 4).

The earthquake has been assigned various magnitudes, e.g., M=7.5 (Gaulon et al., 1992), m_b=6.5 and M_s=7.2 (Girder and McConnel, 1994), M_s=7.1-7.4 (Giardini and Beranzoli, 1992). The focal parameters (depth, seismic moment and focal mechanism) by various international agencies and research groups (e.g. NEIC, USGS, CMT, MEDNET, and GEOSCOPE) as well as researchers e.g. Gaulon et al. (1992), Giardini and Beranzoli (1992) display some similarities as well as significant differences especially in the focal depth. We would like therefore to point out that, whatever the criteria used to determine the focal parameters, focal depths for most crustal earthquakes are not quite reliable when conventional techniques are used. Consequently, the purpose of this study is not necessarily to resolve the existing disparities in focal parameters but rather to re-evaluate the focal depth and to undertake a reassessment of the seismotectonics of the northern/central parts of Kenya and southern Sudan based on results from this study and historical earthquake records. Further, a new goal for this study is to attempt to reproduce the rupture pattern of the May 20, 1990 earthquake and subsequently relate this to the seismotectonicsin this region.

3. METHODOLOGY AND DATA ANALYSIS

In order to perform the waveform inversion so as to determine focal parameters for the May 20, 1990 southern Sudan earthquake, digital broadband seismic waveform data was extracted from Global Seismographic Network (GSN) of Incorporated Research Institutions for Seismology (IRIS) webpage for both II and IU networks. In order to improve the results and final solution, additional broadband seismic waveform data was also obtained from the above webpage for various other seismic networks such as China Digital Seismograph Network (CD), Digital Standardized Seismographic Network (DW), GEOSCOPE (G), German Regional Seismic Network (GR), and MEDNET Project (MN).

For this study, twenty three (23) seismograms from nineteen (19) seismic stations characterized by good signal-to-noise ratio were selected.The distances for theseismic stations were limited in the range of 30° to 100° from the earthquake epicenter. This distance range is appropriate so as to make use of stable seismic rays travelling mostly in the lower mantle which are free of complexities caused by reflection or refraction in the upper mantle and near the core-mantle boundary (Yoshimoto and Ando, pers comm.). The P-wave seismograms consist of the direct P wave and the depth phases $_pP$ and $_sP$. The horizontal P-wave seismograms were rotated to generate transverse (SH) components as discussed by Kikuchi and Kanamori (1991). The digital broadband seismic waveform data for P- and SH- components was then equally sampled at 10-20 Hz sampling frequency, and synthetic seismograms for P- and SH- components generated by summation of normal modes at periods of 80 seconds for both synthetic and observed seismograms as discussed by Kikuchi and Kanamori (1991). Observed and synthetic seismograms for P- and SH- components were then band-pass filtered between 0.02 Hz and 1 Hz. This frequency band provides a convenient characterization of the rupture process for teleseismic source spectrum (Houston, 1990). A weighting scheme for the synthetic and observed seismograms was introduced and time correction computed for each observed seismograms so as to match their P- and SH- phase onset times with that of the synthetic seismograms.

Inversion of P- and SH- waveforms was then undertaken as discussed by Kikuchi and Kanamori (1991); Kikuchi et al., (1993) and, Thio and Kanamori (1996). The first step of the waveform inversion was computation of theoretical Green's function using the generalized ray method (Helmberger, 1983) and the global average earth velocity model of IASPEI91 (Kennett and Engdahl, 1991). The initial value of focal depth (14.9 km) given by USGS/NEIC was used for the starting model and the theoretical Green's function was then computed during inversion by variance minimization using a trial and error approach (Kikuchi and Kanamori, 1991; Kikuchi et al. (1993). For this first step of the inversion, the best result was obtained by using eleven (11) discrete depths at intervals of 2.8 km. This ensured that the focal depth was varied from a shallow 0.9 km to 28.9 km, hence covering almost the entire crust. During the inversion, the fault plane was represented by nodal pointsequally spaced at 40 km in the strike direction.

Earthquake source-time function was obtained by deconvolving the vertical component of teleseismic P-waveforms with the impulse response (source-free) synthetic seismograms. The source-time function was parameterized into a sequence of two overlapping isosceles triangular elements having a total base length of 13.2 seconds and time increments of 6.6 seconds. Inversion of the seismograms to retrieve initial focal mechanism (fault plane solution), seismic moment, moment magnitude, strike, dip, rake, rupture start time, location of rupture front, as well as variance in focal depth was then undertaken by minimizing the misfit, in a least squares sense, between observed and synthetic seismograms. Figures 7a and 7b show the results of the first step of P- and SH- waveform inversion.

A more robust second step of the waveform inversion involved only the P- waveforms. The earthquake source parameters were modeled as point double couple with a time dependent source time function (Kikuchi and Kanamori, 1991). For this study, the source time function was parameterized into a sequence of six overlapping isosceles triangular elements each having a base length of two seconds, and time increments of one second. Other variable parameters incorporated in this stage of inversion were strike, dip, rake, focal depth and rupture start time of the initial rupture (main sub-event) as obtained from the first step of the inversion. Additional parameters included rupture front velocity (V_r) and the fault plane represented by a grid scheme in kilometers in x- and y- directions.

Figures 5a and 5b show the final results of the robust inversion obtained by inverting only the P-waveformsas discussed in the preceding paragraph.

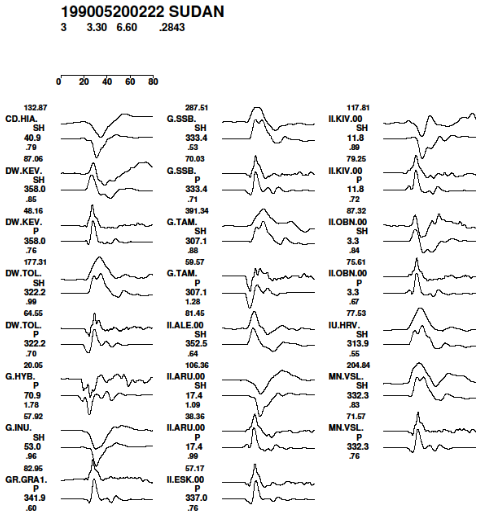

Figure 4a: Observed and synthetic P- and SH- waveforms used during the initial stage of the inversion processes where the upper and lower waveforms are the observed and synthetic seismograms respectively (After Mulwa, 2011).

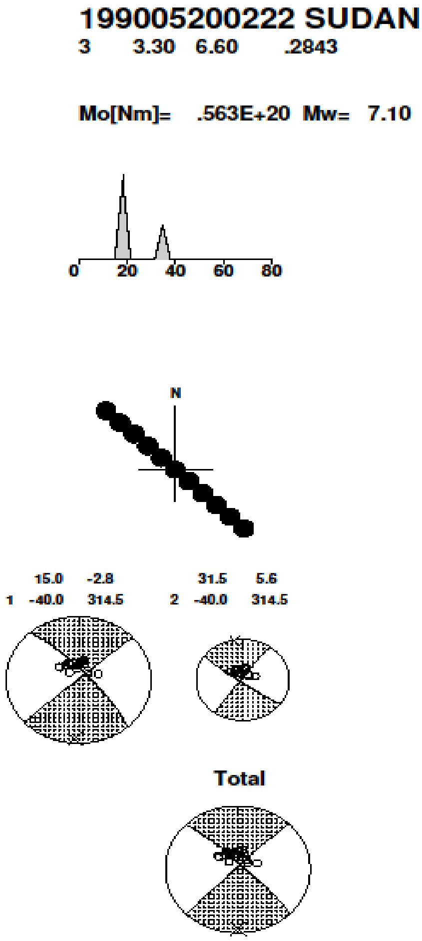

Figure 4b: Source time function, fault plane and focal mechanism obtained from inversion of P- and SH- waveforms in figure 4a (After Mulwa, 2011).

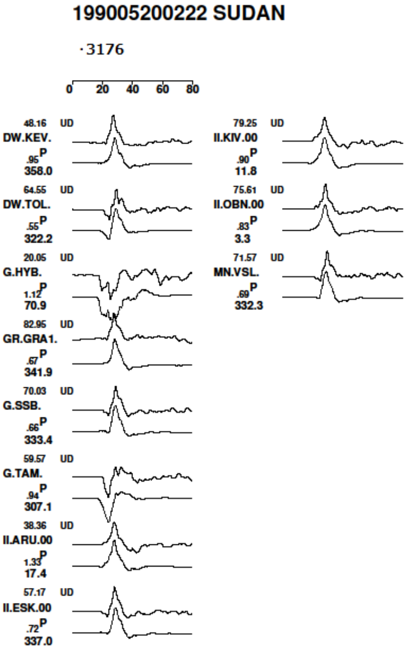

Figure 5a: Observed and synthetic P- waveforms inversion using the robust inversion technique where the upper and lower waveforms are observed and synthetic seismograms respectively (After Mulwa, 2011).

4. RESULTS AND DISCUSSION

The results of inversion of P- and SH- waveforms (Figure 4b) shows that the main shock due to the May 20, 1990 southern Sudan earthquake consists of two sub-events (1 and 2) along a fault plane striking 314.5^{o}. The source duration and focal depths of the two sub-events are 15.0 seconds and 12.1 km (sub-event 1) and 31.5 seconds and 20.5 km respectively.

The results of robust inversion of P- waveforms however, show that the best solution of teleseismic body-wave inversion of the May 20, 1990 southern Sudan earthquake consists of only one event (Figure 5b) with a source mechanism of $315^{o}/84^{o}/-3^{o}$ (strike/dip/rake). The focal mechanism is predominantly strike-slip and the fault rupture pattern demonstrates that the strike-slip fault mechanism is left-lateral. The focal depth for this earthquake is 12.1 km, seismicmoment $M_o = 7.65 \times 10^{19}$ Nm and moment magnitude, $M_w = 7.19$ (≅7.2). The source duration due to the May 20, 1990 southern Sudan earthquake is 17 seconds along a fault plane having dimensions of length ≅60 km and width ≅40 km, as deduced from the source-time function and rupture pattern respectively. An average dislocation of 1.1m along the fault was obtained from the inversion results and the calculated stress drop, $\Delta\sigma$, based on equation by Fukao and Kikuchi (1987), is 1.63 Mpa.

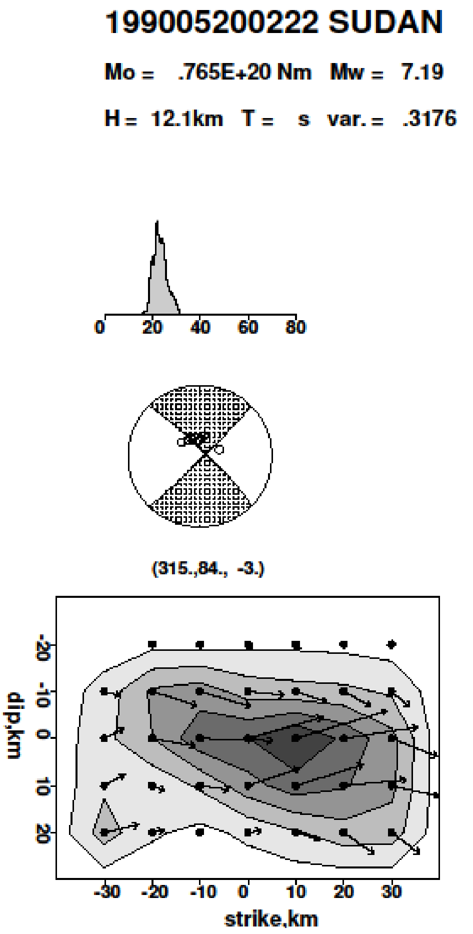

Figure 5b: Source-time function, focal parameters and fault rupture pattern obtained from robust inversion of P- waveforms (After Mulwa, 2011)

Figure 6 shows the focal mechanism, seismic moment and focal depth for this earthquake as determined by various international agencies, individual researchers and research groups. The results of this study as well as those from other international agencies, research groups and individual researchers show that the Centroid Moment Tensor solutions, which are routinely computed for earthquakes of M ≥ 5, over-estimate the source depths and durations, especially for shallow (crustal) earthquakes. The focal mechanism (fault plane solution) as well as focal depth determined in this study is consistent with that determined by USGS. Further, the focal mechanism from this study is also similar to that determined by Gaulon et al. (1992).

Babiker et al. (2010) have noted that the seismicity in the southern part of Sudan is associated with extension of the western branch of EARS into Sudan. The results of this study however demonstrate that the May 20, 1990 earthquake is not related to extension of the western branch of EARS into southern Sudan but rather to re-activation of the NW-SE trending Aswa shear zone which extends into Kenya as Aswa-Nyangia fault zone.

According to Dindi (1994), Anza rift zone in northern Kenya, which trends parallel to Aswa shear zone, dips southwestwards. From the results of this study, the direction of dip of the main fault at the epicenter is 84° SW. Consequently, we can infer that the two fault zones developed due to similar stress regimes.

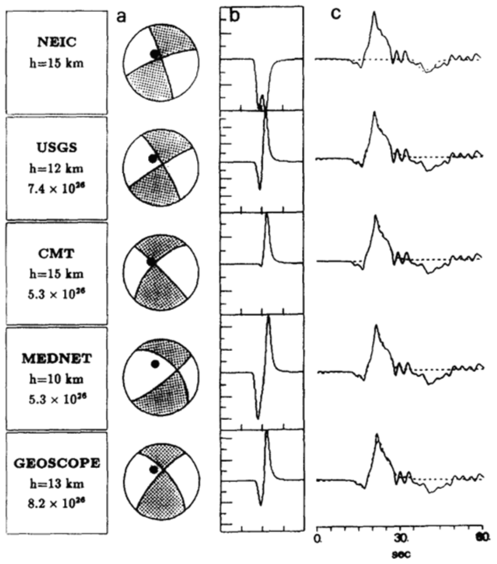

Figure 6a: Focal mechanism, seismic moment and focal depth of May 20, 1990 earthquake determined by various agencies and research groups (After Giardini and Beranzoli, 1992).

$M_o = 8.2 \times 10^{19}$ Nm

Figure 6b: Focal mechanism, seismic moment and focal depth for the May 20, 1990 earthquake (After Gaulon et al., 1992).

Figure 7 shows the distribution of historical earthquakes, $M_w \geq 5.0$, from 1900-1930 on the eastern part of the African continent. It can be seen from the figure that the northern and central parts of Kenya and southern Sudan have experienced strong earthquakes whose epicenters are aligned in a NW-SE direction. This NW-SE alignment of epicenters (Figure 2) confirms existence of a seismically active fault zone trending in a NW-SE direction. However, owing to lack of waveform data for the historical earthquakes, it is not possible to determine their source mechanism.

Consequently, the strike slip fault mechanism for the May 20, 1990 southern Sudan earthquake determined in this study as well as by various international seismological agencies and individual researchers strongly supports inference for an existence of a NW-SE trending intra-continental transform fault zone which extends from southern Sudan to central Kenya rift valley. This transform fault zone has apparently been the site of strong earthquakes in the past. Local earthquake data derived from the Kenyan seismic network and supplemented by historical earthquake records (Figure 3) show that this fault/shear zone probably extends further southeast into the Indian Ocean. However, further work such as inversion of short-period waveforms is required so as to determine the focal mechanism and possibly confirm and support this inference on the SE extension of the transform fault zone.

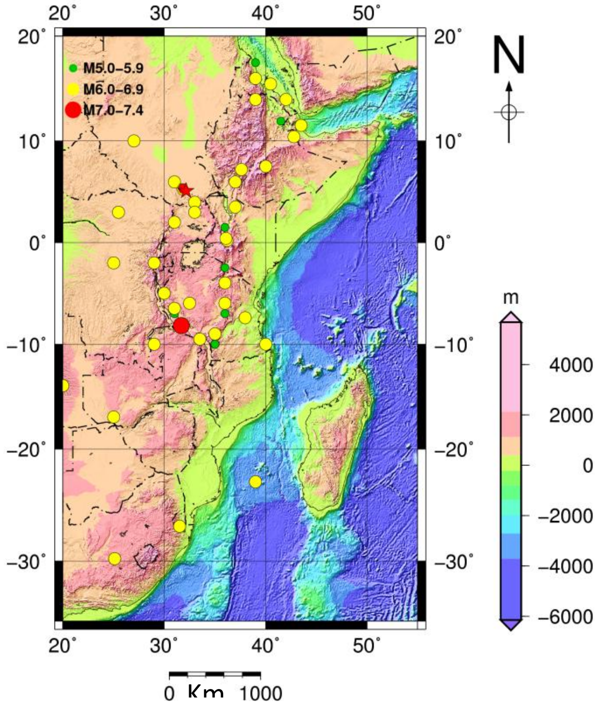

Figure 7: Earthquake epicenters for some historical earthquakes ($M_w \geq 5.0$) on the eastern part of African continent from 1900-1930.

5. CONCLUSION

Modeling of teleseismic body waves for the May 20, 1990 earthquake shows that the focal mechanism is purely strike-slip with a strong left-lateral component on a fault plane striking 315^o (NW-SE) and dipping 84^o SW. The earthquake fault plane solution (focal mechanism) strongly indicates re-activation of Aswa shear zone rather than northward extension of the western branch of East African Rift Valley into Sudan. The strike direction of the fault zone is fairly consistent with the fault rupture direction and the rupture propagated in a more or less southeast direction along the fault plane with dimensions of 40 km by 60 km in width and length respectively. The stress drop due to the May 20, 1990 earthquake on this fault area is 1.63 Mpa. The calculated average dislocation is 1.1 m and the source-time function shows that the source duration due to the May 20, 1990 southern Sudan earthquake is 17 seconds. The focal depth was relatively shallow at 12.1 km. The seismic moment released by the earthquake is 7.65 x10^{19} Nm, which corresponds to a moment magnitude of 7.2.

Epicentral distribution of historical earthquakes supports a strong inference for a NW-SE extension of a transform fault zone from southern Sudan through central Kenya and further SE into the Indian Ocean. This will, however, require further work involving inversion of short period waveforms so as to determine the source parameters of the local earthquakes.

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