Africa Journal of Physical Sciences Vol. 8, pp. 137-144, November 2024
http://uonjournals.uonbi.ac.ke/ojs/index.php/ajps
ISSN 2313-3317

SEISMICITY EAST OF THE SOUTHERN KENYA RIFT VALLEY, KENYA

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ARTICLE INFO

Article History:
Received: July 2024
Accepted: August 2024
Available online: November 2024

Keywords:
Seismicity
Seismic source zones
Seismic Hazard

ABSTRACT

A new seismicity map that accounts for the seismic behavior, tectonic complexity, and potential seismic hazards in the eastern part of the southern Kenya Rift Valley is presented. The results are based on the analysis of 224 earthquakes recorded for 103 years, from 1917 to 2020, with magnitudes ranging from 2.5 to 5.6 M_w, confirming moderate to high seismicity and subsequently moderate to high-stress levels. Data from fifteen catalogs is collated and homogenized; magnitudes are unified to M_w. The seismicity is diffuse with pockets of seismic clustering, delineating seven seismic zones, namely the Simba-Mutito zone, Oloitokitok-Kimana-Chyulu zone, Mzima Springs-Mashetani Lavas zone, the Yatta-Voi zone, the Tertiary-Quaternary sediments (north) zone, the Tertiary-Quaternary sediment (south) zone, and the Mwananyamala-Davie fracture zone. Seismicity does not sorely straddle the surface faults; this is attributed to the reactivation of buried faults oriented northwest-southeast, north-south, and northeast-southwest. Further, the study infers an east-west trending shear zone running from the Mzima Springs and across the Yatta shear zones to the coastal sediments. We affirm that the seismicity is not confined to the Southern Kenya Rift but extends off the rift eastwards, re-emphasizing the need for comprehensive seismic monitoring and hazard assessment beyond the main rift zones.

ISSN 2313-3317

1. Introduction

The occurrence of moderately large earthquakes off the Kenya Rift Valley east of the Southern Kenya Rift has continued to elicit concerns and research interest over the years [5], [12], [37], [39]. The east southeastern Kenya Rift zone consists of topographically high areas, including the Chyulu and the Taita hills, and the largest mountains in Africa, Mt. Kilimanjaro, rising to 5,895m overlooking the low-lying Yatta plateau and sedimentary basins stepping down to sea level at the Kenyan coast.

The earliest reported and documented seismic activity was felt west of the Tsavo River in 1918 [7], [6]. Later, diffuse seismicity east of the Kenya Rift Valley is reported within the tertiary and quaternary volcanic and is associated with a decreasing lithosphere-asthenosphere boundary [39]. The area northeast of Mt Kilimanjaro is confirmed to exhibit seismicity prominence [5], [12], 16], [36] and [39].

A list of notable earthquakes east of the southern Kenya Rift Valley (see Table 1) includes the M 5.5 offshore Mombasa in 1990, Mb 4.2 in 2006 Inland from Mombasa in 1994, M 4.9 in Takaungu, Mb 4.0 in 2011 in Kinango Kilifi, Mb 4.9 in 2007 Kwale, M 4.2 in 1991, Mb 4.8 in Wundanyi in 2019, and M 4.0 in 2011 in Malindi [10], [11].

Table 1: Significant event in the area southeast of Kenya [10] [11]

Date	Origin	Latitude	Longitude	Mag	
1990-03-13 23:05:19	Mombasa	-3.994	39.925	5.5	29 km NE of Mombasa
1995-02-27 12:22:24	Takaungu, Kilifi	-3.836	39.763	4.9	26 km N Mombasa
2006-06-17 21:53:08	Mombasa	-4.134	39.728	M_b 4.2	11 km SE Mombasa
2007-12-23 12:50:13	Kinango, Kwale	-4.043	39.253	4.9	Not given
2008-02-14 15:31:02	Shimoni, Kwale	-4.804	39.306	4.5	45 km south of Kwale
2019-03-24 16:21	Wundanyi	-3:07	38:188	M_b 4.8	41.2 km to Wundanyi
1995-12-08 23:40:40	Mombasa	-4.474	38.794	5.0	107 km Mombasa
2017-02-05 09:54:40	Mombasa	-5.029	39.256	4.5	Not given
2011-05-29 03:08	Malindi	-2.505	39.503	4.0	Not Given
2012-04-17 02:01	Makueni	-2.141	37.544	4.5	38 km from Makueni

The recognition of off-rift seismicity occurring east of the southern Kenya Rift Valley confirms the presence of seismicity and the tectonic complexity leading to considerable seismic hazards. It further suggests that broader tectonic processes beyond the main rift structure can influence seismic activity. Therefore, a study of the seismicity east of the southern Kenya Rift and its associated seismic characteristics delineating seismic source zones will improve the understanding of the off-rift seismicity and associated tectonic complexities.

The main objective of this investigation was to collate, homogenize, and analyze all available catalogs and associated structural and tectonic data sets to better understand the seismicity, the seismic sources, their distribution, and seismic hazard implications. This focused research utilizes data sets derived from seismicity catalogs and recent structural and tectonic sources, including recent publications, to generate a new seismicity map giving seismicity spatial and temporal distribution, delineating seismic sources and their implications for seismic hazards.

2. Geology, Structural and Tectonic Setting

2.1 Geological Setting

The Geology east of the southern Kenya Rift Valley region (Fig.1) encompasses three major geological formations, namely, the Neoproterozoic Metamorphic Belt [19] [33] [34] [38] [40], the Tertiary and Quaternary volcanic rocks marked by the Mt Kilimanjaro, Chyulu Hills, Simba Hills as well as the Yatta plateau. The Tertiary and Quaternary to Recent sedimentary sequences are doted by minor intrusions of the Post-Jurassic age igneous rocks. The Neoproterozoic Mozambique Belt is a geological and structural unit within which various metamorphosed sedimentary and igneous rocks show broad concordance in structural style. The dominant characteristic feature of the Neoproterozoic Mozambique Belt (900-550 Ma) is its structural trend, which is N-S to NW-SE along the Yatta and the Mutito Shear [27]. The Yatta shear zone is presumed to originate as a sub-

vertical wall of a laterally climbing central thrust zone during the Pan-African collision, with reactivation during post-collision history progressively transferred to the Mutito fault [27. The Taita hills are situated in the Mozambique Belt and form a major Upper Proterozoic to the Lower Paleozoic structural metamorphic unit [30] [31]. The Taita Hills are composed of Precambrian paragneisses, representing metamorphosed pelitic, arenaceous, and calcareous sediments with intercalations of bare igneous rocks. The structural evolution of the Taita Hills took place in three deformation phases. The Taita Hills are marked by an angular conformity to the sedimentary sequence [26].

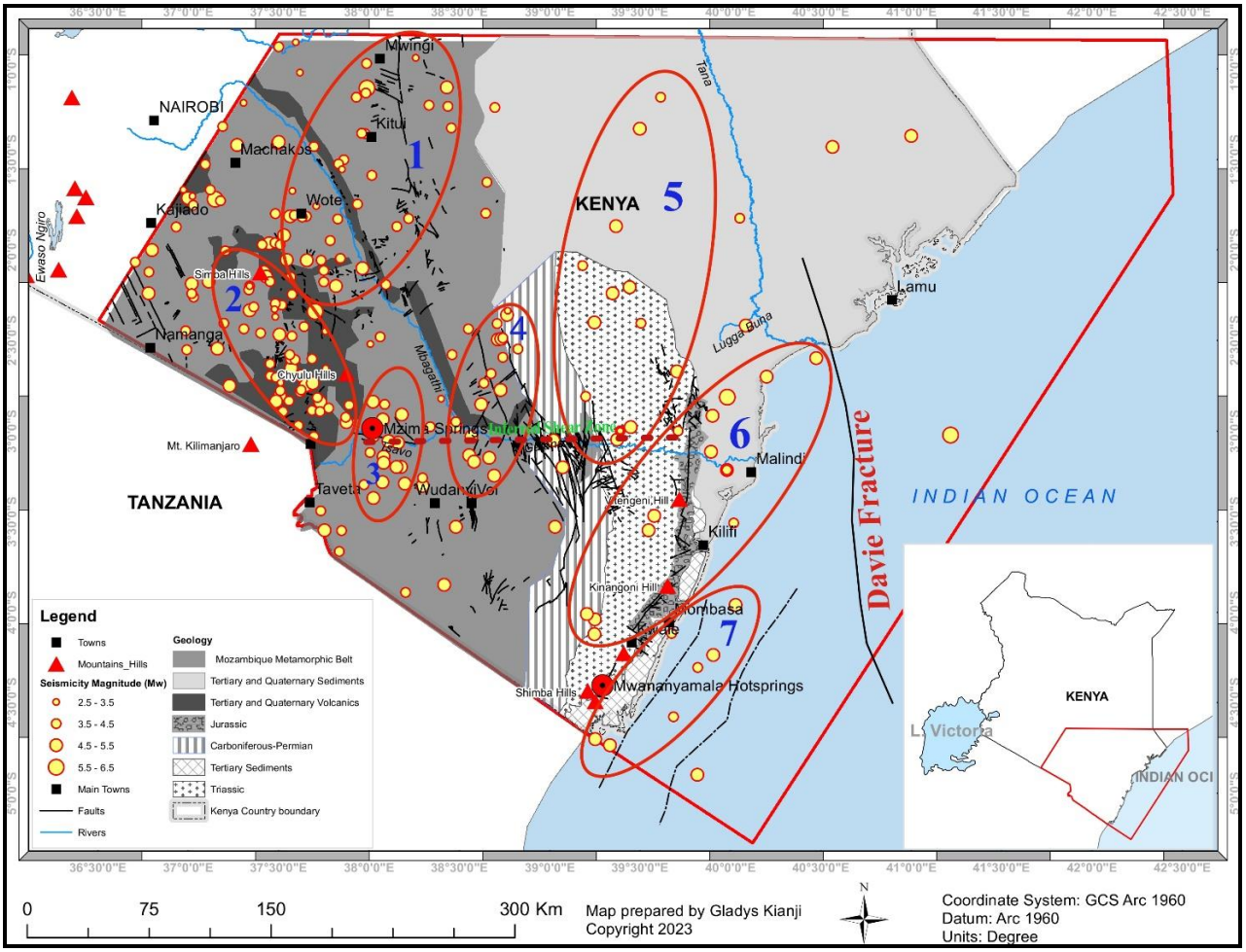

Figure. 1 The seismicity map for the area east of the southern Kenya Rift. Seismicity (yellow circles with red rims) overlaid on an updated geological and structural map modified from [8] [9] [17] [23] [29] [30] [31] [33] [35] and [40]. The delineated seismicity source zones (large red circular shapes) are labeled in blue (1-7). The inferred Mzima springs-Yatta shear zone runs E-W (in red dashed line).

Towards the coastal region, four volcanic hills, namely the Shimba, Vitengeni, Kinango, and Jombo hills, dot the terrain. In addition, the Mwananyamala geothermal field extends 44 km^2, straddling the faulted Permo-Triassic sandstones [22]. The hot springs discharge slightly alkaline NaC1-$NaHC0_3$ waters. Maximum surface discharge temperatures are 56°–76°C with calculated reservoir temperatures of between 172°–180°C [26]. The geological history of the Palaeozoic and Mesozoic sediments in coastal Kenya is linked to the evolution, faulting, and subsequent rifting and uplift of the Kenya dome during the break-up of Gondwanaland in the Mesozoic Era [3]. The extensional

regime of the coastal Karoo basin terminated in the Jurassic when the basin was tectonically sealed off.

2.2 Structural and Tectonic Setting

The Neoproterozoic Mozambique belt runs predominantly north-south (N-S, while northwest-southeast (NW-SE) orientations dominate surface faults present. The area is dominantly overlain by the Neoproterozoic Mozambique Belt rocks with two exceptions: i) The Chyulu Hills and the Yatta shear zone dominated by tertiary volcanic and ii) The Indian Ocean coastline were Tertiary and Quaternary sediments about 8 km in thickness are encountered [1], [18].

The KRISP 90 passive seismic experiment results indicated P-velocity perturbations in the lithosphere underneath the Chyulu Hills. A lateral velocity contrast of about 5% with a prominent low-velocity zone directly beneath the Chyulu Hills volcanic range down to 70 km depth is noted [13], [24], [25]. At depths greater than 70 km, the low-velocity zone (LVZ) shifts towards the east, away from the volcanic field within the crust and upper mantle [14], [32]. Crustal thickness is about 40 km around the Chyulu Hills and thins towards the Indian Ocean to 22 km [24] [25]. Early sedimentary basins in the Kenya Rift Valley, part of the Gregory Rift Valley, were nucleated on northwest-southeast (NW-SE) and north-south (N-S) trending weaknesses. As the plume ascended and spread laterally, rifting propagated away from this zone, and younger basins developed across both mobile belts and cratonic crust [35]. Within the Karoo between the Jurassic and the Triassic, it has been established that the N-S trending fault with alternating northeast-southwest (NE-SW) and northwest-southeast (NW-SE) strike direction exists and implies recent faulting. The Davie Fracture Zone extends from the Lamu embayment off the coastal zone in Kenya (Fig 1). The relationship of this structure to Madagascar suggests that it was a fracture that could have controlled the break-up and motion of Madagascar as it drifted southwards to its present position.

3. Material and Methods

This research entailed data sets, including available historical and instrumental catalog data. A detailed geological and structural map from recent publications has been compiled. The seismic data sources include catalogs, bulletins, and publications for the area east of the southeast Kenya Rift region. Among the catalogs used is the International Seismological Centre (ISC) catalog, which was searched using the event catalog on 25 May 2021, in addition to individual catalogs covering the area. A comprehensive literature review was also carried out. Data was processed and analyzed for each catalog to determine quality and completeness using a prepared MATLAB script. Priority was given to data and events recorded by specialized research works and international networks/data centers, followed by regional and local catalogs. Where a local catalog contains a good quality data set, it is prioritized. As part of the catalog unification, coordinates and magnitudes were homogenized to one coordinate system. All data was converted to the moment magnitude M_w preferred because it directly indicates the seismic moment magnitude. Surface wave magnitude M_s, when converted to magnitude $M_{w,}$ yields a similar relation to M_L [4]. Generally, an updated seismicity catalog compiled from different reliable sources and recent geological and structural maps formed the basis of this interpretation.

4. Results and Interpretations

The main result of this study is an updated seismicity map comprising two hundred and twenty-four (224) earthquakes with moderate magnitudes ranging from 2.5 to 5.6 M_W spanning 103 years. The seismicity patterns straddle all major geological formations: The Tertiary and Quaternary volcanic, the Tertiary and Quaternary sediments, and the Neoproterozoic Metamorphic Belt rocks (the Mozambique belt). Further, the seismicity is not aligned with the surface structural and tectonic trends except for a diffuse but somewhat linear seismicity trend delineating seven seismic source zones. The seven seismic source zones delineated include the Simba-Mutito zone, the Oloitokitok-Kimana-Chyulu hills zone, the Mzima Springs-Mashetani zone, the Voi-Yatta zone, the North-Tertiary and Quaternary (North) zone, South-Tertiary and Quaternary (South) Zone, and the Mwananyamala-Davie Fracture Zone. The seismicity infers buried faults and fault zones orientated dominantly in northeast-southwest (NE-SW), north-south, and northwest-southwest (NW-SE) directions. Additionally, a shear zone is inferred trending east-west (E-W) from Mzima Springs through the Yatta shear zone to the coastal region. The study confirms that the seismicity is largely tectonic with a minor volcano-tectonic contribution. The seismicity also aligns with known geothermal manifestations, namely the Mwananyamala hot springs south of the area close to the coastal region.

5. Discussion

The seismicity of the area east of the southeast Kenya Rift Valley is donated by seismicity ranging from 2.5 to 5.6 Moment Magnitude (Mw), implying moderate to high seismicity [12]. A considerable number of earthquakes are also reported by international and regional networks and publications [5] [12] [16] [17] [21] [28] [36] [37] [39]. Relatively large events are recorded, and the lack of small events below Magnitude 2.5 Mw is attributed to poor seismic network coverage. The presence of local and regional stations as part of the contributing networks confirms that the reported and calculated location and magnitude are representative with minimal location errors.

Apart from the area northeast of Mt Kilimanjaro, which exhibits a clear cluster of seismicity, the seismicity is diffuse in most other areas, with clusters forming and straddling the Tertiary and Quaternary volcanic of the Chyulu hills, the Mt. Kilimanjaro and the Mashetani lavas. These volcanic centers form northwest-southeast (NW-SE) trends that conform to the early proto segments trend northwest-southeast (NW-SE) and manifest in tandem with the orientation of offshore major faults and lineaments, implying African structure inheritance [17]. Semi-linear seismicity is observed at the Oloitokitok-Kimana area parallel to the Chyulu hills and the Mzima Springs. This seismicity is presumed to relate to the buried faults on the footwall of the Chyulu Hills fault. There is also a marked structurally controlled seismicity along the Arthi River and its tributaries. At the Tsavo River, an east-west trend indicates a structural control and possible termination of the Yatta Shear Zone.

Observed diffuseness of seismicity and moderate to high magnitude in the area indicates considerable high-stress levels off the Kenya Rift Valley. While there are no dominant linear seismicity patterns, the clustering of events implies pockets of active zones trending in three dominant directions: the northwest (NW), north-northwest (NNW), north-south (N-S), and

northeast (NE). The dominant faulting mechanism is perpendicular to the dominant north-northwest south-southeast (NNW-SSE) to north-south (N-S) trending active faults, considered older than the northeast (NE) trending faults.

South of the Yatta Shear Zone and close to its associated right lateral kink [19], a second set of north-south seismicity cuts through the volcanics and along the unconformable strata boundary between the Neoproterozoic Mozambique Belt and the Tertiary and Quaternary sediments. Moderately large isolated earthquakes are more significant than 5.0M_w and straddle the Mutito Shear and Davie Fracture Zones.

Structurally, the seismicity within the volcanic and the Mozambique belt is clustered with the north-northeast (NNE) trends. In contrast, in the Tertiary and Quaternary sediments, the seismicity is sparse and marked by moderately large earthquakes greater than 5.0 M_w. Seven seismicity source zones are identified as the Simba-Mutito source zone, the Oloitokitok-Kimana source Zone, the Chyulu Hills source zone, the Mzima springs-Mashetani lave source zone, the Tertiary and Quaternary sediments source zone, the Mwananyamala hot springs to Davie Fracture zone.

6. Conclusions

A seismicity map of the east southern Kenya Rift Valley (KRV) area, comprising 224 seismic events with magnitudes ranging from 2.5 to 5.6 Moment Magnitude (M_w), is presented. The moderate to high seismic activity confirms that the area exhibits moderately high regional stress. Diffuse distribution of seismicity and clustering around volcanic centers and fault lineaments confirm that both tectonic and volcano-tectonic processes influence seismic activity. Limited structural and morphological manifestations add to the complex tectonics of the area where the seismicity is not entirely confined to surface fault lines but mainly to the reactivation of buried faults oriented northwest-southeast, north-south, and northeast-southwest. Seven seismic source zones are delineated as follows: The Simba-Mutito zone, the Oloitokitok-Kimana-Chyulu zone, the Mzima springs at the tail end of the Chyulu Hills, close to the Northeast end of the Mashetani lava, the Voi-Yatta-shear zone, Tertiary and Quaternary (north) sediments, Tertiary and Quaternary (south) sediments and the Mwananyamala–Davie fracture extending offshore the Kenya coastline. The study infers an east-west trending shear zone from the Mzima Springs and across the Yatta Shear Zones to the coastal sediments.

7. Recommendations

i) A dense network of seismic stations should be installed to collect more data for detailed seismic analysis and monitoring and precisely delineate buried fault lines and zones.

ii) There is a need to carry out a detailed structural mapping and delineate the extent of active faults such as the Davie fracture and the Mutito shear zones.

Acknowledgment

The author conceptualized the idea, methodology, analysis, and write-up. This research includes the German Academic Exchange (DAAD), the University of Nairobi, and the International Science Program (ISP).

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