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The Seismicity of the Nyanza Rift: Implication for its Propagation from the Main Central Kenya Rift Valley

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Abstract

A new seismicity map of the Nyanza Rift is presented, using a compiled and unified earthquake catalog of 290 earthquakes spanning 107 years from 1913 to June 2020 and magnitude $M_L \leq 5.2$. A magnitude of completeness Mc 4.0 and a *b*-value of 0.74 confirm that the Nyanza Rift Valley is an active extensional rift. The seismicity patterns confirm that the Nyanza Rift propagates in a WSW direction off the main Central Kenya Rift. The Nyanza Rift lacks, to a large extent, bounding structural controls eastwards of Lake Victoria, implying that Lake Victoria sits in half-graben, except at the Winam Gulf, where the active Kisumu faults, Nyando faults, and Kendu faults bound imply a graben. The seismicity predominantly diffuses and straddles the entire length of the Nyanza Rift, about 250 km, with a breadth of 50 km. Six active faults are identified: The Nandi fault, Kisumu fault, Nyando fault, Kendu fault, Lambwe-Samanga fault, and the Siria-Vitumbara fault. Earthquake depths increase southwestwards, where lower crustal earthquakes 30-38 km confirm crustal thickness increases within the Tanzanian Craton and underneath Lake Victoria. Four seismogenic source zones are delineated as the Tinderet-Timboroa Zone (Zone-1), the Winam Gulf and Homabay-Rangwe Zone (Zone-2), the Southeast Lake Victoria Zone (Zone-3), the Siria-Vitumbara Fault Zone (Zone-4). Within seismogenic source zones, Zone-1 to Zone-3 a north-northeast seismicity trend is observed, implying possible re-activation of buried faults.
Keywords: *Seismicity, Seismicity patterns, Seismogenic source zones, West-southwest propagation of the Nyanza Rift Valley*
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1. Introduction

The Kenya Rift System (KRS) runs from North to South and changes its propagation direction to NNW-SSE at Central Kenya Triple Junction. In this section, the Nyanza Rift Valley, an East-West aligned and structurally controlled valley leading to Lake Victoria, intersects the central Kenya Rift Valley (Shackleton, 1951). Numerous East African Rift system studies have shown that continental rifts can also develop within cratons (Katumwehe et al., 2015; Fletcher et al., 2018). Katumwehe et al., 2015 show that the Neogene age (~20 Ma) magma-poor Albertine-Rhino graben that represents the northern segment of the western branch of the EARS extends for ~200 km in an NE-SW direction within the Archean-Paleoproterozoic age Northeast Congo block, which means the northeastern extension of the Congo craton. Other rifts that mimic the NE-SW direction included the Eyasi and Manyara segments Mulibo et al., 2012 and the Lake Kivu region (Devaux et al., 2022).

The seismicity and propagation of the Neogene Nyanza Rift Valley from the Kenya Rift Valley and the Winam Gulf are poorly understood (Kianji, 2003). The problem at hand is whether the Neogene age Nyanza Rift Valley which bifurcates off the Main Central Kenya Rift is active and how it propagates off the Central Kenya Rift (Fig.1). Several studies have confirmed that the Nyanza Rift Valley is seismically active (Sieberg, 1932; Loupekine, 1968; Tobin et al., 1969; Molnar and Agrawal., 1971; Shah., 1986; Ambrasseys, 1990; Ochieng, 1993; Kataka, 1995; Hollnack & Stangil, 1998; Kianji et al., 2004). Moderately large earthquakes have been recorded, including M 5.4 on September 1st, 1957, M 5.2 on August 14th, 1955, and M 4.9 in March 1968. In March 1968, a one-year-long series of earthquakes shook Homabay town, causing one death and extensive minor damage to buildings and structures. Further, Loupekine, 1968, confirmed this to relate to the movement of the Lambwe-Samanga faults. McGill, 1972 recorded activity from the Siria-Vitumbara faults and the northern boundary faults of the Winam Gulf Rift Zone. The north boundary faults of the Winam Gulf Rift. In 1971, Durham University installed the Kaptargat Network and recorded seismicity associated with the boundary faults of the Winam Gulf.

Later, from 1993 to 1998, Hollnack and Stangil, while investigating the seismicity of the Southern Kenya Rift, recorded activity at the Siria-Vitumbara and similar seismicity associated with the northern boundary faults of the Winam Gulf. The Nyanza Rift Valley is geologically heterogeneous and primarily impacted by the Craton structure westwards (Mboya, 1981; Mathu, 2000). Some considerable seismicity is associated with the Nandi escarpment; subsequently, the Nandi fault is presently considered a massive fault with its fulcrum at Mt Elgon as its escarpment decreases gradually towards the fulcrum (Mathu, 2000). The Nandi fault is further considered a Precambrian shear zone that continues into Uganda as the Aswa-Nandi Shear Zone (Mathu, 2000). Immediately off the Triple Junction in Central Kenya, the Nyanza Rift Valley is covered by volcanic, mainly phonolites, showing east-west flow patterns. The Nyanza Rift Valley continues as a structure 50 km off the central rift, changing direction from east-west to northeast-southwest at the Winam Gulf (Jones and Lippard. 1979; Mboya, 1983; Pickford, 1982). Detailed tectonics and structural controls along the length and breadth of the Nyanza rift are necessary, except for the Winam Gulf area, which exhibits a pronounced graben.

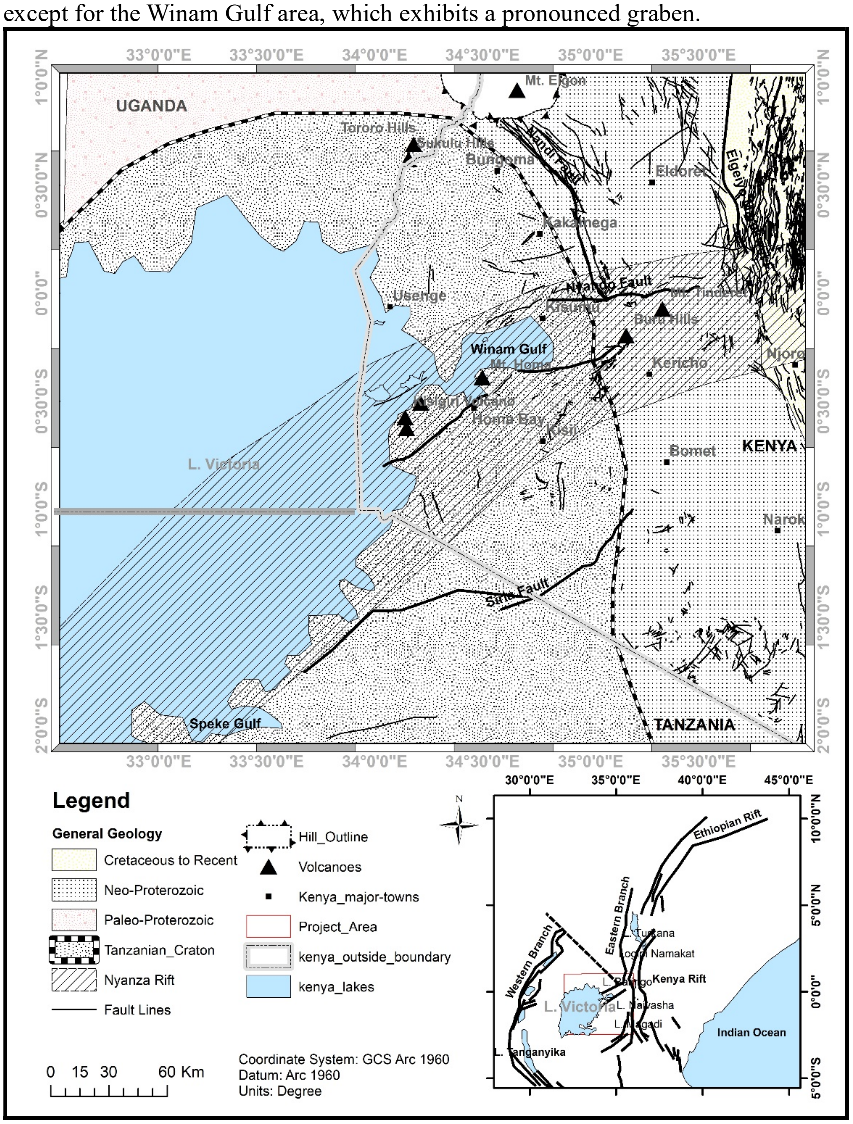

Figure. 1. The location map of the Nyanza Rift Valley

Poor seismic station coverage and isolated incomplete catalogs covering short periods have formed the basis for previous limited and generalized attempts to quantify the seismicity of this young rift. The elevation of Kisumu to City status, coupled with a population increase, has seen sprawling infrastructural development horizontally and vertically within the Nyanza Rift Valley. One cannot ignore the seismic hazard and associated risk related to the proximity to this seismic hazard. Over the last few years, several data sets and catalogs have been made available, together with recent tectonic and structural studies covering the Nyanza Rift Zone and comparable areas elsewhere. Despite lacking data from a localized and well-distributed seismic station within the Nyanza Rift Valley, we investigate how seismically active the Nyanza Rift Valley is and how it propagates, its hazard implication to hazard using an up-to-date catalog, geological, tectonic, and structural data, and maps.

In recent years, there has been a significant increase in the number of focal mechanisms available for the entire rift system, and it is now possible to estimate the present-day stress field in relative detail based on seismotectonic data alone (Devaux, 2010). Though limited, the available focal mechanisms in Table 2 give insight into present-day stress in the Nyanza Rift Valley. This study, therefore, aims to compile, unify, synthesize, and interpret datasets to understand the seismicity and its implications for the propagation of the Nyanza Rift Valley.

The East African Rift Valley (EAR) and its relationship with the Kenya Valley (inset lower left figure) are plotted on a simplified geology map (main figure). The upper figure of the Nyanza Rift Valley is the presumed propagation of the Nyanza Rift (stripped) and volcanic centers (black triangles) modified from Mboya et al., 1981; Pickford et al., 1982.

2.0 Geological and Tectonic Setting

2.1 Geology of the Nyanza Rift Valley, Kenya

The Geology of the Nyanza Rift Valley is influenced by the Tanzanian craton (Fig. 1(a)), within which Lake Victoria rests. Geology mainly comprises the supra crustal rocks of the Archean Nyanzian meta-volcanic and the Kavirondian meta-sediments. The Pre-Miocene floor of the region consists of gneiss (Basement System) in the east, separated by the Nandi fault from the altered bare igneous rocks (Nyanzian System) and Post-Nyanzian granitic rocks in the west (Shackleton, 1951). Off the Gregory Rift at the Triple Junction within the Central Kenya Rift, the Nyanza Rift is occupied by a Phonolitic flow following an E-W flow pattern. This activity only extends to the Nyanza Rift except for the section around the Timboroa area where, from about 20-7Ma, there was an accumulation of a thick pile of Nephelinitic and Phonolitic volcanics. From 7 Ma to the present, volcanic and tectonic activity progressively concentrated in the axial zone of the Kenya Rift. This period is inactive volcanically within the Nyanza Rift (Jones, 1979). The Tinderet volcano occurs towards the eastern end of the Winam Gulf within the Nyanza Rift. The Tinderet Zone and the Rangwe/Kisingiri volcanic complex are two present volcanic flows. Geologically, the Tinderet volcanic flows are mainly lavas overlying the Neoproterozoic Mozambique basement gneisses. The Mozambiquan basement regional structure presents north-northwest with steep dips to the northeast. The Elgeyo plateau is vast and has a uniform, gently dipping nature, suggesting a fissure probably related to the Elgeyo escarpment fault trend. The Tinderet zone is bounded by the Nandi fault, which runs north-northwest and it emerges beneath the volcanic rocks of Mt. Elgon., (Gibson, 1954) and disappears into the south Nandi Forest (Huddleston, 1954; Binge, 1962) and reemerges to cross the Nyando Scarp before its disappearance beneath the alluvium of the rift valley plains (Shackleton, 1951., Binge, 1962) were it is interpreted as a fault (Mathu, 2000). The Rangwe-Kisingiri volcanic complex comprises the Rangwe Caldera Complex, other Homabay volcanic centers, and the main Kisingiri volcanic complex. The Kisingiri comprises Nephelinite and Carbonate and is host to the Rangwe Caldera complex, which was active in the Tertiary (Rosateli, 2023). The Kisumu volcanics are bounded by the Kiniamwia Escarpment, which is part of the Kiniamwia fault. The fault pattern is distinctly antithetic in style in the area's southwest. This set of normal faults strikes SW-NE with downthrows to the north, away from the rift.

2.2 Tectonic Setting of the Nyanza Rift

The morphological and structural field evidence reveals that the rift is not bounded by significant faults downthrown into it for most of its length. The structural deformation of the Nyanza Rift consists of normal antithetic and oblique faults, a monoclinal flexure, and a syncline, confirming the formation of the Nyanza Rift due to crustal extension. The relationships of structures to the deformed rock strata suggest that the Nyanza Rift Valley probably formed from gradual but continuous tectonic movements starting in the early Miocene. Lake Victoria occupies a position between the uplifted border plateaus of the eastern and western branches of the East African Rift System (EARS), which resulted from river reversal and ponding due to rift margin uplift. Ebinger, 1989; Scholz et al., 1990, 1998) also describe it as a 'tectonically induced lacustrine system' (Tiercelin & Lezzar, 2002). The phonolite flow patterns were determined to be aligned in east-to-west and northeast-to-southwest directions. The phonolites covered the area before the final faulting phase, forming the rift (Mboya., 1983). The Nyanzian and Kavirondian are Mesoarchean super group 3.1-2.5 Ga and have a system of isoclinal folds with axes with an east-west trend. The Kavirondian and Nyanzian are greenstone belts rich in gold mineralization but are separated by an unconformity. They are slightly younger than Nyanzian but fold in the two supergroups. The Nyanza rift has been reported to be a classical graben throughout its length (Saggerson, 1970). The Nyando scarp defines the classic graben portion to the north and partly by the Nyabondo fault-line scarp to the south. In the north Winam Gulf area, to the west of this graben sector, the structure of the valley becomes less well defined, and it is replaced by a series of northeast to southwest striking normal fault-line scarps, downthrown to the north (i.e., away from the rift). The structural deformation of the Nyanza Rift, which consists of normal antithetic and oblique faults, a monoclonal flexure and a syncline confirms that the Nyanza Rift Valley is formed through crustal extension (Mboya, 1983). Around the Elgeyo escarpment, we find a fault scarp due to post-Miocene faulting (Shackleton, 1950). The plateau in this part of the Nyanza rift is vast, with a uniform, gently dipping nature, suggesting a fissure probably related to the Elgeyo escarpment fault. A Precambrian shear zone that continues as the Aswa-Nandi Shear zone is seismically active (Nyamai et al., 2003). The Kinematic indicators of the Aswa-Nandi fault point to a sinistral sense of shear, Saalmann, 2015.

The Nyanza rift is more comprehensive to the west (c.50 km) and narrower to the east (c.30 km), Mboya, 1983. Topographical and structural considerations show that the Nyanza Rift largely fades 50 km west of the Kenya Rift and is barely perceptible at its edge. The structures are concealed beneath recent volcanic and sediments (Shackleton, 1951). In addition to numerous faults, tectonic movements associated with the formation of the Nyanza rift gave rise to a monocline in the west and a syncline in the southeast.

3.0 Data and Methods

3.1 Earthquake Catalogues Unification Prioritization

An updated microseismic and instrumental seismicity catalog for 1913 to 2020 (107 years) comprising 290 earthquakes 1.0 to 6.2 M_L is compiled. The quality of each catalog is checked using a prepared Matlab script before the unification of Magnitude. An up-to-date map is prepared using ArcGIS software. From the analysis, a catalog of 290 events was prepared and used for the seismicity of the Nyanza Rift Valley, Fig. 2 below. The seismicity displays a west-to-south-west trend right through its entire length of approximately 250 km. The seismicity follows a west-southwest trend off the Kenya Rift Valley and splays southwards in a southwest direction through the central part of the study area. Off the Nyanza Rift Valley, scattered, isolated earthquakes occur.

3.1.1 Instrumental and Non-Instrumental Catalogues

Seventeen catalogs generated the datasets as follows: Seven (7) local catalogs, one regional and one (1) (international catalog, with Nine (9) international agencies contributing part of the ISC catalog (see Table 1) contributing the data for the catalog. Some of the authors are Ambrasseys, 1992; Ambrasseys and Adams 1986/1991 contributed 26 (M_b) events; Kianji, 2003 contributed 8 (M_L) events; Gill 1971, who contributed 97 (M_L) events; Langston et al. 1995 contributed 50 (M_L) events; Albraic et al., 2007, who contributed 3 (M_L) events; Weinstein et al., 2017, contributed 26 (M_L) events. All these, including the International Seismological Center (ISC), contributed 290 events after removing duplicates and declustering using Gardener and Knoppof, 1954 equation in ZMAP. The magnitudes vary from 2.5 to 5.2 M_L from all the data collected. Two groups of depth clusters are noted at 0-15 km and 23-40 km depths. The deep events are mainly located within the craton beneath Lake Victoria.

The reviewed ISC catalog is used as a priori data sets, giving 145 earthquakes. The priority was given to ISC-Gem events, which provide re-analyzed events, followed by ISC/ISC-EHB, which offers improved locations. The local catalogs were prioritized as follows: Gill, 1971, followed by Langston et al., 1995; Kianji, 2003; Albraic et al., 2007; and Hollnack & Stangil, 1998. The Ambrasseys 1992 and Ambrasseys and Adams catalogs were used directly because there was no other comparison.

Table 1. Summary of available earthquake catalogs giving number of events contributed by each catalogs.

No	Catalog/Author	No/Events	No	Catalog/Author	No/Events
1	Gill et al., 1972	97	10	Kianji, 2004	8
2	ISC/EAF	54	11	ISC/ISC-GEM	3
3	Langston et al., 1998	50	12	Algebraic et al., 2007	3
4	ISC/ISC	30	13	ISC/IDC	3
5	Ambrasseys, 1992/ Ambrasseys & Adams (1986/1991)	26	14	ISC/PRE	3
6	Weinstein et al., 2017	26	15	ISC/LSZ	2
7	ISC/BUL	12	16	ISC/EIDC	1
8	ISC/NAI	24	17	ISC/ISC-EHB	1
9	Hollnack & Stangil., 1998	8		TOTAL	290

3.1.2. Catalog unification to Local Magnitude (M_L)

Most of the magnitudes are reported in M_L by the majority of agencies. The M magnitude for BULL and LSZ are retained as concerns are raised regarding their determination (Devaux et al., 2022). The LWI magnitude is converted to M_b (USGS) using the equation by Mavonga and Durheim, 2009, (Eqn. 1) before reconversion to local magnitude. For M_s Waeatherhill et al., 2016, Eqn. 2 while to convert Mb to ML, Gutenberg, and Richter 1954, Eqn. Three and Eqn. 4. To Moment magnitude (M_W), the Schodrillis equation for intraplate domains Eqn.5 is used.

M_b (USGS) = 0.282M (LWI) + 3.315 (Mavonga and Durheim, 2009) Eqn. 1
M_s (ISC) to M_b(ISC) to M_w=0.764 (+/-0.04) M_D+1.379 (Waeatherhill et al., 2016). Eqn. 2
M_W=0.616Ms+2.369; (Ms, </-6) M_W=0.944+01; (M_s>6) M_W=1.084M_b-0.42; (M_b<6.5)

M_b=1.8+0.73 M_L (1< M_L<6) (Gutenberg and Richter, 1954) Eqn. 3
M_b=1.27(M_L-1)-0.016M_L^2 (Gutenberg and Richter 1954) Eqn. 4
M_W=0.722M_L+0.743; M_L>2 for intraplate domains (Schodrillis, 2006). Eqn. 5

Independent events (foreshocks and aftershocks) were removed from the updated catalog by specifying a window in space and time using the Gardener and Knopoff 1974 in Zmap. This clustered the catalog from 301 events to 290 events.

3.2 Seismic source areas and characterization within the Nyanza Rift Valley, Kenya.

Seismicity patterns delineate four seismicity zones constrained by the geology and, to a lesser extent, the tectonics of this region. Z-Map software is used for the frequency magnitude distribution (FMD) of the Nyanza Rift Valley. Seismic source zone Zone-1 (Tinderet-Londiani Zone), the Winam Gulf /Homabay-Rangwe Zone (Zone-2), the South East Lake Victoria Zone (Zone-3), and the Siria-Vitumbara fault Zone (Zone-4). The Frequency Magnitude Distribution for each zone is shown in (Table 2), and inference to the stress regime is determined. Seismicity Zone-1 is the east-west trending zone immediately off the triple junction where the phonolite lavas were extruded in a north-east and north-northeast south-southwest direction. In this zone, seismicity has been associated with the re-activation of buried north-northeast south-southwest trending faults related to the basement system (Gill, 1972). Similarly, the zone is cut by the active Nandi Fault to the East, which forms the westerly boundary with the Tanzania Craton, where the boundary faults are pronounced. Seismicity Zone-2 comprises the Winam Gulf and the Homabay volcanic complex. The southern part of the Nyanza Rift Valley lacks a structural boundary except in the Winam Gulf, bounded by the Kisumu, Nyando, and Kinamwia faults. The seismicity of the Homabay-Kisingiri volcanic complex, at least in the Homabay area, is not controlled by the visible faults but instead exhibits a north-northeast trend across the boundary faults, implying the re-activation of buried faults. The seismicity in Zone-3 lies east of Lake Victoria, where the easterly bounding faults are mainly lacking. The seismicity equally follows a north-northeast direction. Seismogenic zone-4 represents the Siria-Vitumbara faults, which lie parallel to the Nyanza rift and could be the locus of a young rift formation, implying a parallel half graben to the Nyanza rift.

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4.0 Results and Discussions

4.1 Results

A catalog of 290 events is generated, and an updated seismicity map is prepared, showing that the Nyanza Rift Valley is active and propagates in a west-southwest direction. The seismicity is moderate, with a magnitude range from 2.5 to 5.2 M_L within the Nyanza Rift Valley, with a large magnitude of M_L 6.2 (Fig.2.) immediately off the area close to the Central Kenya Rift Valley. Small events below M_L 2.5, with one outlier and M_L 1.0, are lacking, probably due to poor station distribution.

The Tinderet-Timboroa Zone (Zone-1) is located northeast of the Nyanza Rift Valley, immediately off the Central Kenya Rift Valley, Triple Junction. This Zone-1 dots fifty (50) earthquakes with a magnitude of 2.5 to 5.2 M_L from 1928 to 2010. The depth of the earthquakes defaults to 10 km for most catalogs, with a few calculated depths of up to 26.0 km. The Winam Gulf Zone/Homabay-Rangwe Zone (Zone-2) is located west of the Nandi Fault Zone. The zone is highly faulted and exhibits subsidence dominated by standard synthetic and antithetic faulting. A Frequency Magnitude Determination (FDM) for sixty-two (62) earthquakes with magnitudes ranging between 2.0 to 5.6 M_L results in a *b*_value of 1.09 +/-0.28, *a*_value of 5.391, and annual frequency of occurrence of 3.790. The Zone-2, Homabay-Rangwe area has material heterogeneity varying temperature gradients (Gill, 1997; Warren and Latham. 1970), which may have contributed to the swarms and an unusually large *b*_value leaning to the 2.5 threshold. The 1968 swarm's activity for about twelve (12) months caused by the volcanic heterogeneous structure may have contributed to elevated *b*_value. The area southeast of Lake Victoria, denoted by Zone-3, locates 50 earthquakes and exhibits more diffuse seismicity splaying into a broader zone in a northeast-southwest propagation direction. The data set spanning about 40 years up to 2010 returns a M_c 4.0, *b*_value of 1.06+/-0.13, an *a*_value of 6.015, and an annual frequency recurrence of 4.349. This high b_value shows a weak crust connected to heterogeneous stress systems within the Homabay-Rangwe zone. Seven (7) earthquakes from well-constrained catalogs show deep earthquake depths of 28-40 km within Zone 3. The Siria-Vitumbara Fault Zone (Zone-4) contains 50 events that return a low *b_valu*e of 0.79+/=0.10, *a_value* of 4.564, and an annual frequency of recurrence of 2.798. The depth ranges in Zone-4 is 0.0 to 15.0 Km, with three earthquakes at 36.0-38.0 km that straddle Tanzania southwestwards to the craton towards Lake Victoria.

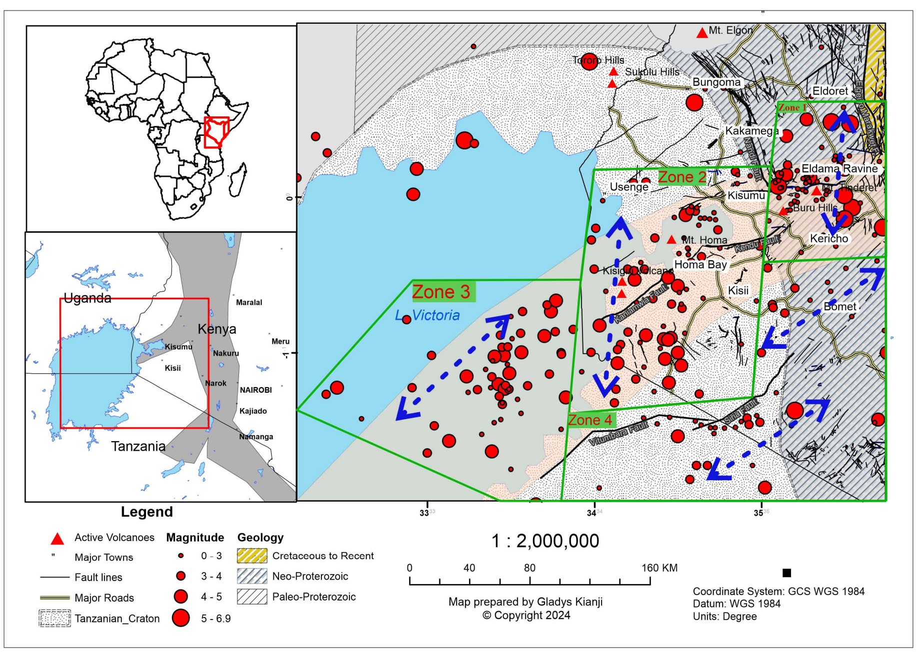


Figure. 2. The Nyanza Rift Valley study area. On the left, the seismicity (red gradational circles) is underlain by geology (see legend). The delineated into four seismogenic zones (green lined zones) with filled labels denoted as Zone-1, Zone-2, Zone-3, and Zone-4 labeled from right to left. The inferred west-south-west (WSW) propagation of the Nyanza Rift Valley (transparent pink zone) and the inferred structural trend deduced from seismicity patterns (blue double sided arrow) imply north-northwest buried faults/fault zones.

Table 2 below gives an overall M_c 4.0, a *b*_value 0.74+/-0.04, *a*_value of 5.158, and an annual frequency recurrence (λ) of 3.153. The five seismogenic zones return the following *b*-values: Zone-1 (0.75), Zone-2 (1.09), Zone-3 (1.52), and Zone-4 (1.06). The b_value for the whole of the Nyanza Rift Valley is 0.79. This overall low b-value implies a tectonic active region like rifts. Gill., 1972, observed comparable results of 0.71+/-0.15 (Wohlenberg., 1969), b-value of 0.85, (Gill, 1972) of 1.12+/-0.1, 5.60, (Hollnack & Stangil., 1998; Kianji., 2003), of 0.8 and a value of 3.66, (Mulwa., 2014), 0.79 and a value of 5.6067 for the Nyanza Rift Valley. Many deep moderate crustal earthquakes are located at the southwest end of the Nyanza rift in the Tanzanian Craton underneath the Lake Victoria area, implying that the crust is thicker and more rigid as one goes in the southwest direction. Also, there are no earthquakes in the lower crust.

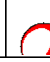
Table 2. Frequency Magnitude Distribution seismicity parameters, including b-values and magnitude of completeness M_c, for all the four zones in the Nyanza Rift Valley.

Z	Zone	No	Period	*b*_value & a_Value	Λ	Depth	Mc	Comments
Zone 1	Tinderet Zone	50	1928-2010	0.75 +/-0.10 & 4.477	2.475	0-15, 26 (2)	3.7	Buried north-northeast trending faults
Zone 2	Winam-Gulf Homabay -Rangwe	65	1913-2018	1.325 +/-0.265 & 6.858	5.488	0-20, 40(2)	4.0	Geothermal volcanic manifestation
Zone 3	Southeast L. Victoria	50	1969-2010	1.06 +/-0.13 & 6.015	4.349	0-15,28-40(7)	4.2	Some Deep events ≠38 km
Zone 4	Siria-Vitumbara	50	1945-2020	0.79 +/-0.10 & 4.564	2.798	0-15, 36-38(3)	3.80	Mainly along the fault line
Area	Nyanza Rift	290	1928-2019	0.74 +/-0.04	3.153	0-38	4.0	Whole area

3.4. Focal Mechanism and Earthquake Depth.

Two focal mechanisms are shown in Table 3. The 2002 earthquake activated one of the faults north of Kisumu, Paleo-Proterozoic faults, separating the Winam Gulf basin from the Mesoproterozoic metasediments. To the southern edge, a normal extension with a sub-horizontal slight oblique focal mechanism for the M_w 5.0 in 2010 formed the southern border faults believed to be Paleo-Proterozoic basement. Depth recalculation was not carried out; instead, the depths determined by specialized local networks were plotted, indicating the location of several moderately deep crustal events located southwest of the Nyanza Rift Valley within the Tanzania craton underneath Lake Victoria. These deep events imply that the crust is thicker and more rigid in the southwest direction and explain the absence or lack of earthquakes in the lower crust northeast of the area. The focal mechanisms generally imply normal faulting with strike-slip motion towards the north-northeast with a sub-horizontal compression and extension.

Table 3. Focal mechanisms for two earthquakes https://www.globalcmt.org.

No	Date/Time	Lat.(°)	Lon. (°)	Dept. (km)	Mag.	Focal Mechanism \(FOC)			
						Strike	*Dip*	*Rake*	*FOC*
1	2002/12/23 02:50:42.1	-1.78	34.69	15.0	M_w5.2, M_b 4.9	225° 317°	59° 85°	175° 31°	
2	2010/6/13 12:13:24.4	-0.15	34.51	12.0	M_w 5.0, m_b 4.9	238° 29°	21° 72°	-62° -100°	

Two fault plane solutions within the study area have been calculated and show that the Nyanza Rift Valley has a normal left lateral oblique fault line around the Winam Gulf Rift and a right lateral strike slip within the Siria-Vitumbara fault Zone. The Focal mechanisms confirm the varied orientation and, hence, the complexity of the Nyanza Rift Valley Zone.

4.0 Discussion

This study has generated a new seismicity map of the Nyanza Rift Valley with 290 earthquakes spanning 107 years, confirming that the Nyanza Rift is seismically active. This confirms that the Nyanza Rift Valley exhibits considerable seismicity, which has been underestimated over time, Hollnack and Stangil, 1998; Kianji, 2003. Poor station distribution has also contributed to the poor understanding of the seismicity. This shortcoming, notwithstanding moderate earthquakes with a magnitude range from 2.5 to 5.2 M_L within the Nyanza Rift Valley itself and in its vicinity events of Magnitude M_L- 6.2 and subsequent Subukia earthquake of 1928, 6.9 Ms, means that the seismic and hazard levels are higher than estimated. Though somewhat diffuse, the seismicity reveals patterns with first-order clustering around volcanic centers and the Winam Gulf flanks. On the southwest of Lake Victoria, we see a first-order linear alignment of seismicity interpreted as the westerly extent of the Nyanza Rift Valley, after which the Nyanza Rift Valley extends southwards in a west-southwest direction. Previous studies confirm that large earthquakes are underneath Lake Victoria (Gill, 1972).

The Nyanza Rift straddles a length of about 250 km to sub-parallel faults further; the Nyanza Rift Valley seismicity delineates a narrow zone of 50 km in the northeast as it spans off the main Central Kenya Rift and widens to 100 km in the southwest. The possible extent of these easterly rift faults to the east of the Nyanza Rift Valley is postulated by Ebinger et al., 1997. While the seismicity is isolated, the frequency implies subsurface buried faulting. Off the marked fault zones, earthquake epicenters are more widely scattered and frequently occur in areas where no apparent faults are visible within the Tanzania craton (Ebinger, 1997). This general seismicity propagation direction of the Nyanza Rift System mimics the direction of propagation of the adjacent young rift zones, the Eyasi and Manyara segments Mulibo, 2012, and the Lake Kivu region (Devaux, 2022). As the Nyanza rift propagates into the Tanzanian Craton in Tanzania, southwestward deep earthquakes >30kms are recorded mainly underneath Lake Victoria, confirming findings by Ebinger 1997, that pre-existing heterogeneities in the Archaean crust influenced the orientation of border faults bounding basins. That topography at the base of the lithosphere guided the location of rifting in Tanzania, producing a broader rift zone, Langston et al., 1995. Further, the seismogenic brittle behavior at sufficient depths explains lower crustal earthquakes in East Africa; the lower crust must not only be composed of mafic lithology but also significantly more heat (~100 percent) must come from the upper crust than predicted by the crustal heat source distribution (Langton et al., 1995).

Significantly large events are lacking except for the Subukia, 1928. M_w 6.2, which is located in proximity to the Elgeyo Marakwet fault. This results from the limited stress build-up before material failure (Gill, 1921). The similarity is drawn from studies in the Eastern Rift (the Kenya Rift Valley), where crustal separation and magmatic intrusion are documented (Griffiths, 1971; Baker, 1971). The crustal attenuation and associated heat flow regime, Baker and Wohlenberg, 1969, may reduce the shear strength and increase the plasticity of crustal material, thereby limiting strain buildup before failure.

Evidence from seismotectonic and seismicity attests that four faults are active. These are the Nandi fault, the Lambwe and Samanga fault, the Nyando fault, and the Siria-Vitumbara fault. The fault systems, geology, and seismicity form the basis for delineating the four seismogenic zones. There is heterogeneity in the crust along the entire Nyanza Rift Valley, where seismic clustering is confirmed in some instances, e.g., the Homabay-Rangwe seismogenic zone. The lack of marked fault scarps in the southwest and some seismicity off the presumed length and breadth of the Nyanza Rift fault zone further reveal diffuse seismicity. Buried faults exist outside and within Lake Victoria and southwestward. The westerly dipping monocline structure to the southwest part of the Nyanza rift and its surrounding areas, the Homabay/Rangwe zone, forms the easterly constraint to the Lake Victoria boundary. The activity around this monocline structure is constrained mainly to the easterly direction along its unpronounced flanks and straddles Rangwe/Kisingiri zone, where the Rangwe/Kisingiri volcanic complex and hydrothermal activity leads to the opening of fissures and cracks—a considerable number of small magnitude earthquakes influencing the high *b*-value of 1.52. In comparison, similar high b-values of 1.3 in the Indian Ocean (Gutenberg & Richter, 1954); the Atlantic Ocean *b*-values of 1.4 and 1.7 (Gutenberg, 1954; Francis, 1968), where seafloor spreading is known to be happening correlate well with the value for the eastern rift of 1.12, (Gill, 1972) and the Lake Kivu (Devaux, 2022). On the other hand, a low b-value implies a tectonic active region like rifts. The Nyanza Rift Valley yielded Frequency Magnitude Distribution (FMD) plots, b-values of 0.74, Gill 1972 compared to b-value covering the whole Nyanza Rift Valley b_value of 0.71+/- 0.15, Wohlenberg, 1970, b_value of 0.85, Gill, 1972, b_value of 1.12+/-0.1, Hollnack et al, 1998, b_value 1.09, Kianji, 2003, b_value of 0.8 and a value of 3.66, Mulwa 2014., b_value of 0.79 and a_value of 5.6 for the Nyanza Rift Valley. Within the seismogenic zones, Zone-2 to Zone-4 from the Winam Gulf to the Kenya/Uganda/Tanzania border and below Lake Victoria, the b-values are above 1.0. This may be influenced by the volcano-tectonic heterogeneous nature of the crust in this zone. Zone 1 and Zone 4 imply tectonic extensional regimes with b-values <1.0. This confirms a considerable difference in energy release and subsequent stress levels, which decrease as you move east to southwest of the Nyanza Rift Valley. The Siria-Vitumbara and the Tinderet zones have moderate b-values of less than one and are typical of extension regimes.

A seismic gap is observed between the Winam Gulf zone and the Tinderet zone, implying a failed arm of the Nyanza Rift or a morpho-structural separation from the rest of the Nyanza Rift through the Winam Gulf the Nandi fault part of the Aswa shear Zone. Notably, the seismicity within this Tinderet zone does not conform to the east-west oriented faults of the Miocene-middle Pleistocene period. This seismicity indicates a possible buried seismic source in the basement running north-northeast to South-southwest. Further, Mboya, 1981 proposed that the geological and geomorphological structural styles of the Tinderet Zone suggest that this portion trends to the northeast. The Nyanza Rift Valley evolved by long-term gradual movement with about two episodes of rifting from east-west to northeast-southwest, confirming a sinistral rotation in an anticlockwise direction (Mathu, 2000). We know that during rifting, deformation tends to migrate towards the central part of the basin along many minor faults. Corti, et al., 2013; Keir et al, 2015. Where the rift narrows, ponding of plume material may enhance melting. Keir et al. 2015. The thinner lithosphere is found at the eastern margin of the Tanzanian craton and to the southeast of the basin's surface location. Thinning is used to propose the presence of a Precambrian suture zone within which Eyasi and other basins further south were formed (Fletcher et al., 201). Furthermore, the lithospheric thickness map indicates that the Tanzanian craton is heterogeneous and possibly composed of multiple smaller cratonic fragments. There is a need to map the faults in this area to relate to the seismicity accurately.

5.0 Conclusion and Recommendation

5.1 Conclusion

A new seismicity map of the Nyanza Rift has been produced using a compiled catalog derived from seventeen catalogs. The study confirms that the Nyanza Rift is seismically active. A new catalog comprising 290 earthquakes with magnitude M_L 1.0 to 5.2 for 103 years from 1903 to 2020 is compiled. The study concludes that the Nyanza rift is active with moderate seismicity. The Nyanza Rift propagates for about 50 km in a westerly direction with a similar width before kinking gradually to the southwest direction, controlled by the sinistral motion of the Nandi Shear Zone. Further, the Nyanza rift increases in width to a broad zone of about 100 km. The seismicity splays in tandem with the propagation direction, though remarkably diffuse. Surficial structural or morphological controls do not constrain the southwest part of the Nyanza Rift Valley. The Nyanza Rift exhibits extensional tectonics within the Tanzania craton, marked by crustal heterogeneity southwards from the Winam Gulf and with lower crustal earthquakes upto ≠38 as the Nyanza Rift propagates towards the central part of the Tanzania craton.

The Nyanza Rift Valley propagates in an east-west/northeast-southwest immediately off the main Central Kenya Rift Valley, where seismicity is associated with the re-activation of faults buried below the Londian-Tenderet volcanics in a northeast-southwest direction. Semi-linear sets of seismicity patterns trend in a north-northeast direction through the length of the Nyanza Rift Valley. The seismicity demarcates the low-lying eastern flank of Lake Victoria and the westerly side of Lake Victoria, further supporting the fact that Lake Victoria could be located in a half-graben. From the Nyanza Rift Valley to the southeast, we find the sub-parallel active Siria-Vitumbara fault, which can be interpreted as the shoulders of a sub-parallel half graben away from the Nyanza Rift Valley. A series of faults run in the northwest direction. The Nyanza Rift Valley generally exhibits extensional tectonics and breaks into the Tanzania craton, which is marked by crustal heterogeneity southwards from the Winam Gulf. Deep lower crust earthquakes 30 to 38 km are typical of the Tanzanian craton as the rift propagates southwards.

Four active faults are mapped, including a) the Nandi fault, b) the Lambwe-Samanga, c) The Nyando fault, and d) the Siria-Vitumbara fault. Four Seismogenic zones are delineated, namely: a) the Timboroa-Tinderet Zone (Zone-1), b) the Winam Gulf Zone/Rangwe-Homabay Zone (Zone 2, c) The southeast Lake Victoria Zone (Zone-3), and d) The Siria-Vitumbara fault Zones b_value. The b-values represent a zone of an active tectonic extension zone. The focal mechanisms confirm that the faulting within the Nyanza Rift Valley is not entirely normal. Strike-slip and up-thrust motions imply the possible interplay of the 2nd-order to 3rd-order stress regimes (Devaux, 2010).

5.2 Recommendation

This study recommends localized detailed tectonic, structural, and seismic investigations within the Nyanza Rift for detailed seismicity and seismic source determination. A more precise estimation of the hazard is crucial to address safety measures, particularly in building and construction, and to mitigate against future hazards amplified by the immense infrastructural development in Nyanza and Western Kenya regions. Seismic data must be continuously acquired for monitoring purposes, and the information must be relayed to the stakeholders. This is especially crucial to avert seismic disasters recently experienced in Japan, Haiti, and Turkey, among other places.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability
Data will be made available on request.

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