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# Investigation of macroseismic intensity of the Mw5.9 September 10, 2016 Kagera earthquake: Implications for site effect amplification

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ABSTRACT

The Kagera earthquake of magnitude Mw5.9 occurred on September 10, 2016 at 12:27 GMT, 15:27 local time, with an epicenter located northwest of Bukoba town, in Minziro village close to the border of Tanzania and Uganda. The earthquake resulted in the widespread damage within the Kagera region with an officially announced death toll of 17, many residential structures destroyed, and others damaged beyond repair. Following the earthquake, a macroseismic survey was conducted by interviewing various affected people using macroseismc questionnaires to delineate the distribution of seismic energy and establish the effects of ground shaking. The results of the macroseismic survey indicate variations of intensity values from IV-VIII on the MSK-64 scale with more frequently assigned values of intensity range from VI-VII. The orientation of the intensity pattern is elongated towards the southeast in accordance with the rupture directivity towards Bukoba town, which is in agreement with the orientation of the fault rupture from the focal mechanism and the distribution of aftershocks. The duration of shaking in many localities was observed to be over 20 s, resulting in resonance effects. Both findings of the observed variations of the intensity values and the duration of shaking indicate that site effects, which result in the amplification of the seismic signals, likely played a great role in the damage distribution. The maximum intensity of VIII, which corresponds to the instrumental magnitude of 6.2, differs from the instrumental result of magnitude 5.9 by a factor of 0.3; the difference is attributed to the amplification by site effects within the region. The observed site effects therefore emphasize the importance of reinforcing the buildings, and, in the future, adherence to seismic building codes and specifications in all regions within the East African Rift system (EARS). It is also hoped that the database of the intensity data points from macroseismic survey will be useful in the development of the seismic intensity prediction equation for the earthquakes within the region and for the assessment of the impact on regional seismic hazard and the entire EARS.

## 1. Introduction

The Kagera region suffered widespread damage during the Mw5.9 Kagera earthquake of September 10, 2016, with an officially announced death toll of 17, many residential structures destroyed, and others damaged beyond repair. The ultimate practical aim of seismology is to help protect communities against the damaging effects of earthquakes; thus, it is important to understand the patterns of effects of earthquakes as a function of magnitude, distance, local conditions and other factors. Studying the effects of past earthquakes in terms of macroseismic indicators is therefore an important component of mitigating the effects of future earthquakes. Moreover, macroseismic surveys will continue to play a significant role in seismological practice for the foreseeable future. A macroseismic survey is one of the seismological practices that assists in understanding the distribution of energy and shaking in various regions affected by earthquakes, and how different portions of the Earth respond depending on the nature of the material properties. The survey collects and evaluates non-instrumental data after occurrence of earthquakes such as effects on people, objects, buildings and nature.

Tanzania is a country with a high seismicity rate and lies within the two branches of the East African Rift System (EARS), namely the Eastern branch and Western branch (Iranga, 1992; Nyblade et al., 1996). Every year many earthquakes are felt within its territory (Nyblade et al., 1996) (Fig. 1). Of the two branches, the Western branch has shown the capability of producing larger earthquakes than the Eastern branch (Ambraseys, 1991). The Kagera earthquake of September 10, 2016 occurred at 12:27 GMT, 15:27 local time, with its epicenter located ~200 km from the Western branch of the EARS just northwest of Bukoba town, in Minziro village close to the border of Tanzania and Uganda (Fig. 2). The earthquake was followed by nine aftershocks that continued for three months after the main event with magnitudes ranging from $M_L$ 2.7 to $M_L$ 4.1. The instrumental magnitude

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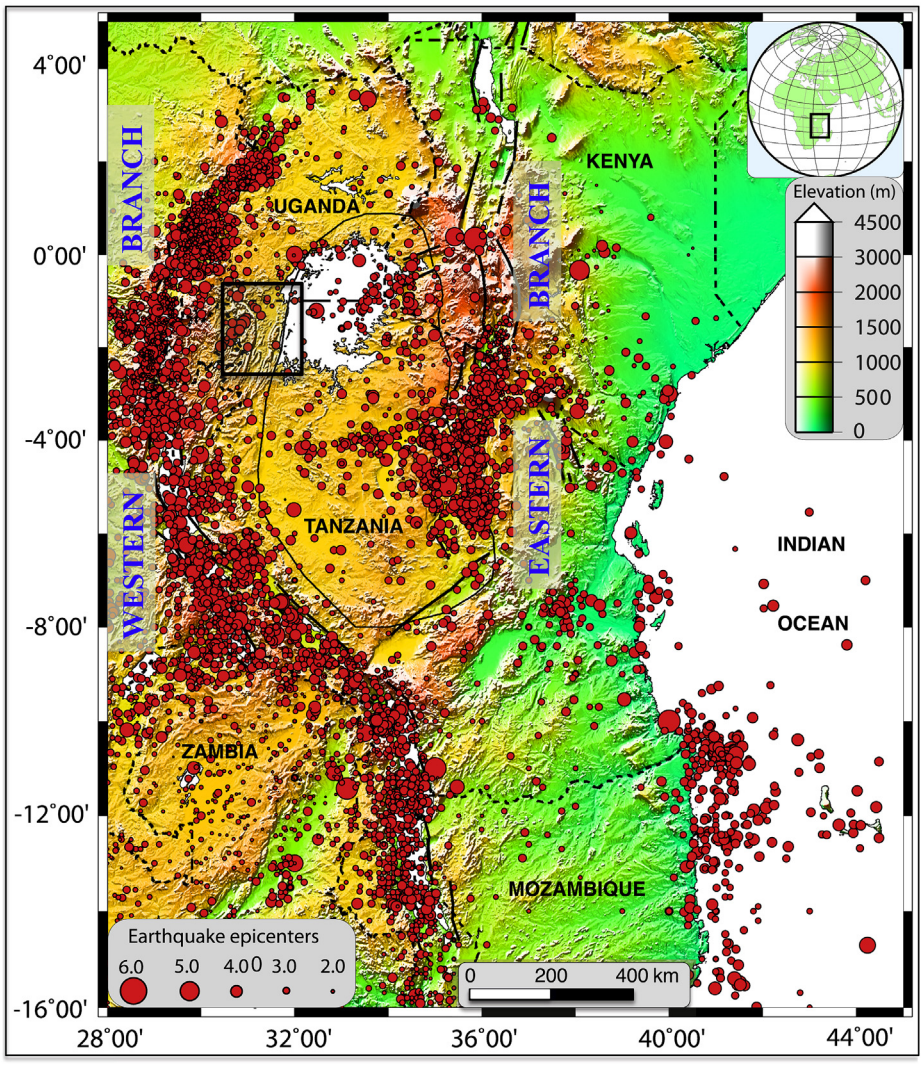



**Fig. 1.** Topography of East Africa showing the location of the East African Rift System, including seismicity compiled from the International Seismological Center (ISC) catalogue for the period between 1900 and 2016, inclusive. The black box shows the region that is enlarged in Figs. 2 and 4 where the Kagera earthquake occurred.

of the main event was determined at Mw5.9, occurred at a depth of about 40.0 km (USGS-NEIC, 2016). It was the strongest earthquake felt in this area during the past few decades and widely felt in neighboring towns and countries. Various news reports suggest that the earthquake effects were strongly felt over a wide part of Bukoba town, which is located at a distance of ~44 km from the epicenter and surrounding areas, including the neighboring towns of Mwanza, Musoma and Shinyanga (Fig. 2). The earthquake was also felt in the surrounding countries such as Kenya, Rwanda and Burundi and especially Uganda (Fig. 2).

Many earthquakes occur within the EARS (e.g., Fairhead and Girdler, 1971; Shudofsky et al., 1987; Kebede and Kulhanek, 1991; Iranga, 1992; Nyblade et al., 1996; Langston et al., 1998) (Fig. 1). However, intensity data from macroseismic survey are not collected for every earthquake, but only for events that cause significant damages and/or fatalities (Ambraseys, 1991). Although macroseismic methods are among the oldest known in seismology (Cecić and Musson, 2004), providing very useful information for damage assessment, it is not common practice in Tanzania. The last macroseismic study to be conducted was associated with the largest recorded historic event in East Africa, the Ms7.4 December 13, 1910 Rukwa earthquake (Ambraseys, 1991). Despite the low level of development and its large magnitude, the earthquake caused very little damage to local types of dwellings and no loss of life, but badly damaged all European-styled stone structure houses along the eastern shore of Lake Tanganyika. With increasing level of development of cities, towns and infrastructure within the EARS, there is now increasing risk posed by the occurrence of earthquakes in East Africa. This study uses data from a macroseismic survey conducted in various parts of Kagera region following the September 10, 2016 Kagera earthquake to investigate the macroseismic effects associated with this earthquake using the MSK-64 intensity scale in order to assess the damage and seismic energy distribution, and its implications for site effect amplification in the region.

## 2. Geomorphology and seismotectonic setting

### 2.1. Geomorphology setting

The Kagera region can be grouped into three geomorphological domains; that consists of the Karagwe-Ankolean region, Bukoban sandtone and Quaternary deposits (Fig. 3). The geomorphology of Karagwe–Ankolean Belt is typified by hill ranges formed by persistent erosion and denudation of the land surface after the onset of crustal movement since Mid-Tertiary time (Quennell, 1956, Fig. 3). The hill ranges, which are made up of resistant quartzite and conglomerates (Fernandez-Alonso et al., 2012), consists of gently undulating uplands

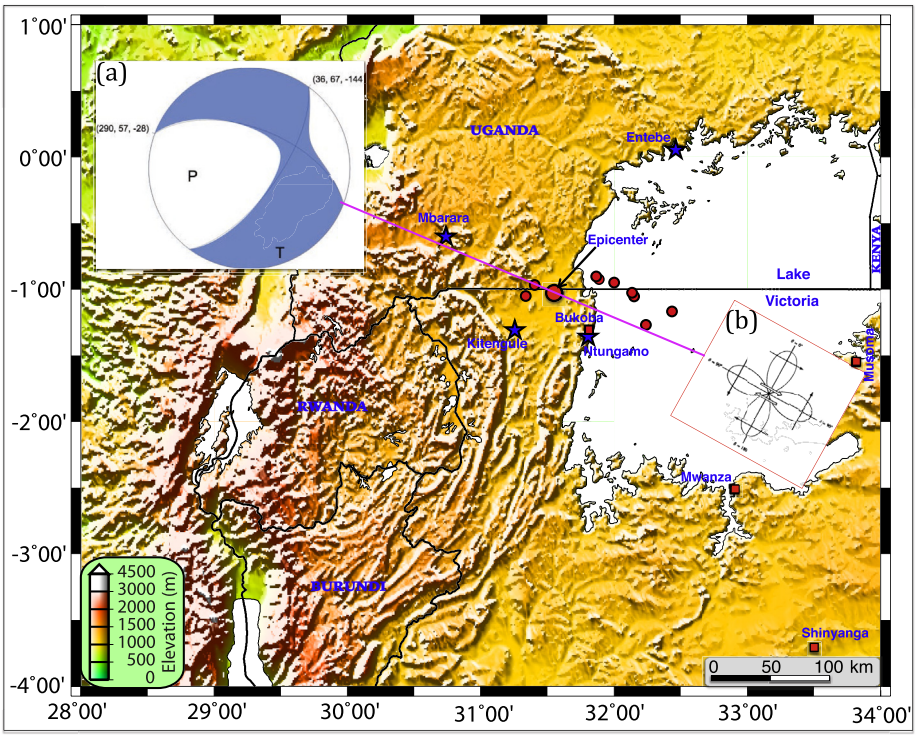



**Fig. 2.** Location of epicenter for the main September 10, 2016 Kagera earthquake (big red circle) and related aftershocks (small red circles). The two inserts are (a) Fault plane solution of the main event computed by GCMT. The letters P and T indicate pressure or compressive and tension principal axes of the seismic moment tensor respectively. (b) The shear energy radiation pattern of the fault displacement. Stars indicate seismic stations near to the main event, where Kitengule and Ntungamo stations were installed after the main event for recording aftershocks for three months. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

as high as ~1450 m above sea level that gradually merge with erosion plains in wide, flat valley floors, which forms the Kagera River basin (Fig. 3).

The Bukoban sandstone is geomorphologically characterized by a series of mountain ridges extending almost N-S, parallel to the shore of Lake Victoria (Fig. 3). The ridge terminates in rugged scarps breaking off in sandstone cliffs. Summits of the ridges are relatively flat, seemingly representing old erosion surfaces (Milne and Savile, 1938) and vary in extent from 1 km to 20 km. The old surface was gradually heaved up and tilted, developing into fault scarps and cut into plateaus and ridges. The current topography of the Bukoban system is strongly controlled by the gently sloping rock strata. Sandstone layers standout

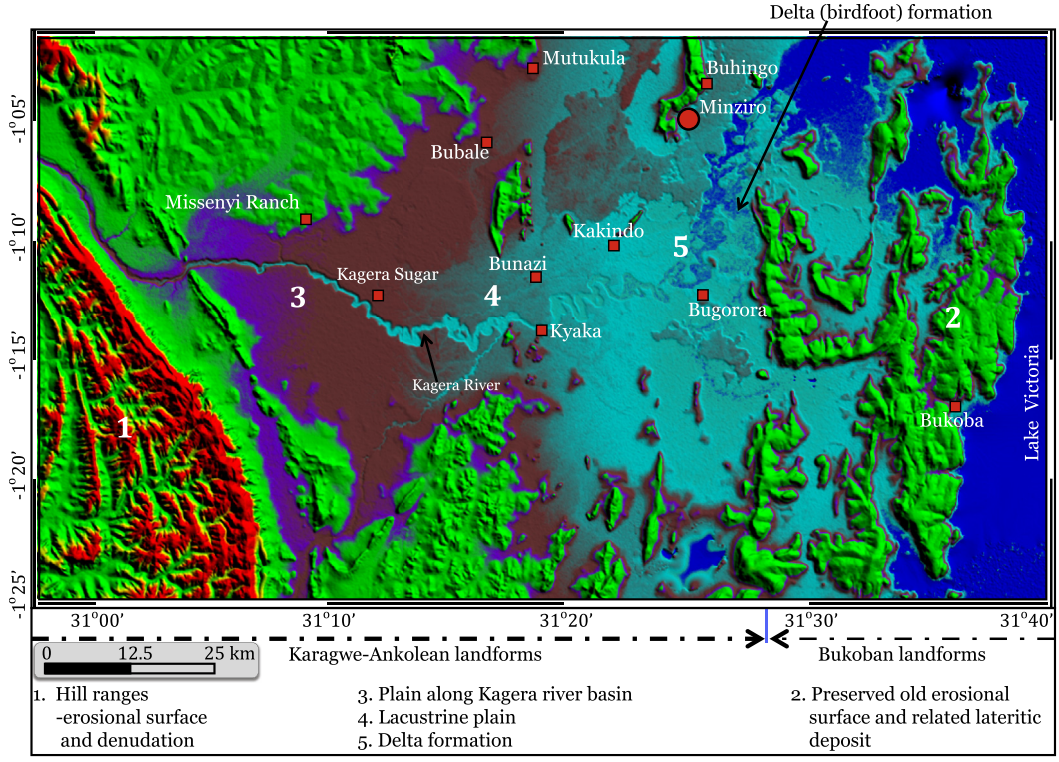



**Fig. 3.** Geomorphology of the Kagera region. The epicenter is shown as a red circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at the surface and form cuesta structures, which are ridges with a steep, short slope on one side and long gentle slope on the dip slope (Touber and Kanani, 1994). The structures record the presence of well-preserved remnants of old erosional surface associated with lateritic deposits in the Bukoban system (Tack et al., 1984).

The landforms of the Quaternary deposits are mainly grouped into three terrains as shown in Fig. 3 (Touber and Kanani, 1994). The first terrain consists of predominantly sandy and gravelly layers represented by floodplains and channel deposits along Kagera river basin located between Missenyi Ranch and Kagera Sugar Estate. The second terrain, which was part of former larger lake, encompasses the lacustrine plain that consists of sandy river terraces merging into a flat, very extensive clay plain. The western shoreline was located between Mutukula and Bubale, with the Buhingo and Minziro hills being islands. The last terrain comprises delta formations near Bugorora, Kakindo and Kyakakela. The Kagera River entered the old lake near the present day Kagera Sugar Estate, depositing its sediments and building up a birdsfoot delta dominated by sandy and silt deposited along the distributary channels.

### 2.2. Seismotectonic setting

The seismicity in East Africa over the past century indicates that the earthquakes are focused in the rift zones, within the Eastern and Western branches of the EARS (Fig. 1) (e.g., Fairhead and Girdler, 1971; Shudofsky et al., 1987; Kebede and Kulhanek, 1991; Iranga, 1992; Nyblade et al., 1996; Langston et al., 1998). Within the Western branch, the highest seismicity rates occur throughout the entire branch from north to south covering the Tanganyika–Rukwa–north Malawi rift segment (TRM) (Kebede and Kulhanek, 1991; Iranga, 1992; Nyblade et al., 1996; Langston et al., 1998; Poggi et al., 2017) and encompassing the Kagera region where the September 10, 2016 Kagera earthquake occurred. Based on seismic hazard zonation, areas of higher seismicity in the Western branch, from north to south, have been divided into subregions, which include (1) the Albertine Rift, (2) the Lake Kivu Basin including the Virunga volcanic area, (3) the Tanganyika-Rukwa- Malawi (TRM) rift segment (including Lake Tanganyika, the Mbeya triple junction and the Rungwe volcanic province), and (4) the Malawi Rift that extends along the seismically active Urema graben towards south Mozambique (Poggi et al., 2017). However, the intraplate seismic activity in Kagera region is relatively sparse; only a few small to moderate events ($2.0 < mb < 5.8$) have been recorded over the past few decades. Consequently, the earthquake hazard was considered to be low.

The stress regime within the Western branch has been investigated in many studies using focal mechanisms (Morley, 1988; Jackson and Blenkinsop, 1993; Camelbeeck and Iranga, 1996; Brazier et al., 2005) and a few studies using kinematic indicators (Delvaux and Barth, 2010; Delvaux et al., 2012) where results show variations of faulting mechanisms, mainly normal faulting and strike-slip faulting. Results for the stress orientation suggest variations in the extension directions either E–W to ENE-WSW (Morley, 1988; Brazier et al., 2005) or NE– SW to ENE-WSW directions (Jackson and Blenkinsop, 1993; Brazier et al., 2005). Other results suggest extension in the NW-SE, NNE-SSW and NE-SW directions (Wheeler and Karson, 1994; Delvaux and Barth, 2010) or sub-orthogonal to the NW-SE rift trend (Delvaux et al., 2012). The results from the analysis of faults in the Lake Tanganyika rift shows that the strike of the primary fault fabrics are rotated in a clockwise direction from the south to north, striking in a mainly NW-direction in the south to a NNE-direction in the south (Muirhead et al., 2018). The September 10, 2016 Kagera earthquake, which is the focus of this study, shows an oblique strike-slip with left lateral movement extending in NNE-SSW direction (USGS-NEIC, 2016).

## 3. Data and methodology

### 3.1. Data collection and field survey

The intensity evaluation through a macroseismic survey using questionnaires in conjunction with the instrumental data, improves the data quality by collecting a large amount of data at low cost and provides observations covering areas close to the epicentre that are likely not found from instrumental records (Mäntyniemi, 2004). The procedure of collecting macroseismic data after the September 10, 2016 Kagera earthquake was to interview various people who were available in the affected area during the incident using macroseismic questionnaires. During the course of the macroseismic survey the observations were compiled into a questionnaire form in order to assign macroseismic intensities using the Medvedev-Sponheuer-Kárnik Scale (MSK-64) (Medvedev et al., 1967). Other additional information from various sources, such as newspaper reports and social media reports, was also used as supplement from the interviews. The interviews were also complemented by physical observations of the damage caused by the earthquake (as classified in Medvedev et al., 1967) and the geology surrounding the area to compare whether the information provided correlates with the physical appearance of the area. In addition, photographs were taken in complicated situation.

It was impossible to make a complete detailed survey and count every house in this exercise. The only way to simplify the exercise while getting enough representative information was to contact the local authorities and identify the sites of particular interest. The sites selected were those identified by local leaders/authorities through the Regional Disaster Committee under the Regional Commissioner. The majority of sites surveyed were public institutions such as schools, dispensaries and health centers together with some residential houses and shopping areas. Six of the eight districts of Kagera region that were reported to have observed damage on structures were involved, namely; Bukoba municipal, Bukoba rural, Muleba, Missenyi, Karagwe and Kyerwa (Fig. 4).

### 3.2. Data analysis and intensity map

Macroseismic observations collected from interviews using macroseismic questionnaires were analyzed covering six districts of Kagera region. The estimation of the macroseismic intensity makes use of the observed damage to buildings and on the human perception of the effect caused by the earthquake and therefore a large sample of observations is important for providing any statistical significance of the evaluations (Bottari et al., 1980). In addition to assigning macroseismic indicators, duration of shaking of the ground and structures was also recorded from the interviewed people. In cases where people did not give reasonable duration times for the earthquake, a time estimate was given based on the actions taken by a person from the beginning to the end of earthquake shaking.

The assessment of the intensity was based on identifying how the various intensities described in the questionnaires best fit all data summed in a particular location (Midzi et al., 2015). This implies that the correct intensity estimation is the one that best expresses the generality of the macroseismic observations (Musson and Cecić, 2002; Cecić and Musson, 2004). Five intensity levels were obtained, ranging from IV-VIII on the MSK-64 scale. The intensity values were shown in the form of isoseismal map, where the values at the surveyed locations were gridded using kriging interpolation technique (Schenková et al., 2007).

## 4. Results and discussion

### 4.1. Intensity distribution and isoseismal map

The overall numerical distribution of intensity levels and duration

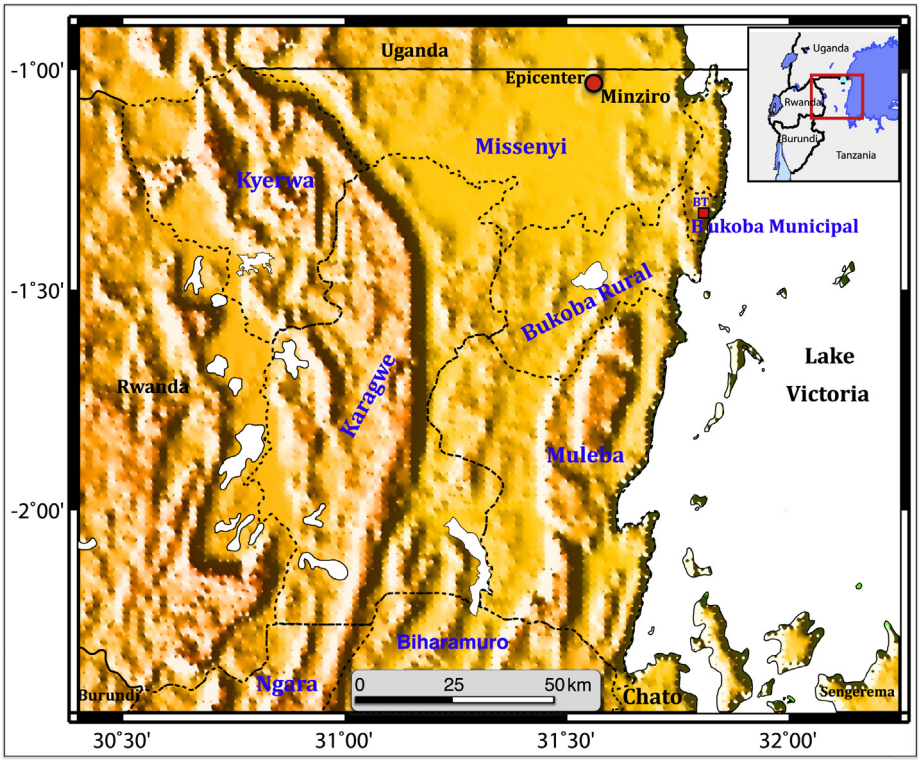



**Fig. 4.** Location of districts of the Kagera region. Six districts (with the exception of Ngara and Biharamuro districts) were reported to have observed damage and were visited for collecting macroseismic information. BT represents Bukoba town.

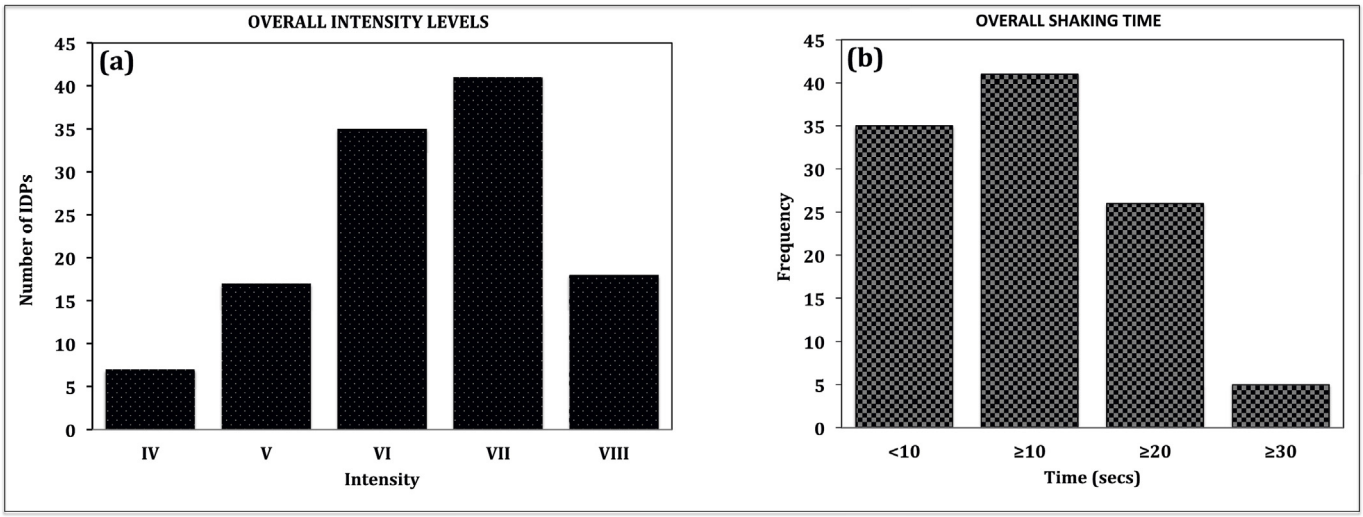



**Fig. 5.** Overall intensity levels and ground shaking time (a) Number of intensity data points (IDPs) obtained for each intensity level (b) Duration of ground shaking sustained in various parts of the Kagera region.

of shaking obtained using the MSK-64 scale coming from all surveyed areas is shown in Fig. 5. It is observed that the highest intensity value obtained was VIII, mostly experienced in Minziro, where the epicenter is located, and in Bukoba town, which is located along the energy propagation direction (Figs. 2 and 5). Fig. 2 also shows that many of the intensity data points (IDPs), 41, had an intensity value of VII. The survey showed that the duration of ground shaking and structural vibration reported in all six districts was generally less than 20 s (Fig. 5b). Most of the duration times exceeding 20 s were reported by people from Bukoba Rural, Missenyi and Karagwe districts and a few from other districts.

The overall distribution of the intensity values from the macroseismic survey is given as isoseismal map in Fig. 6. The orientation of the intensity data points on the isoseismal map is elongated towards the southeast from the epicenter, in accordance with the rupture directivity, which was towards Bukoba town. This is in agreement with the orientation of the fault rupture from the modeled focal mechanism and the direction of energy propagation (USGS-NEIC, 2016, Fig. 2). The faulting mechanism indicates a double couple source with the two nodal planes oriented NNE-SSW and WNW- ESE. In addition, the NW-SE orientation of the macroseismic pattern is also supported by the distribution of aftershocks, which were recorded by seismic stations at Ntungamo and Kitengule (Fig. 2 for station locations). The stations operated for three months and nine aftershocks were recorded with

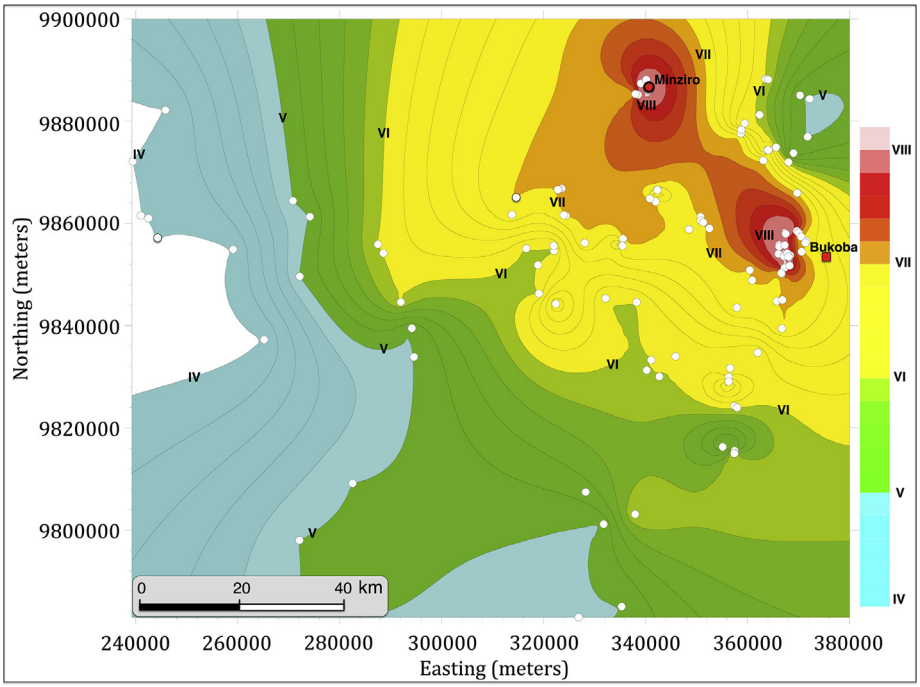



**Fig. 6.** An isoseismal map of the September 10, 2016, Kagera earthquake. The epicenter is shown as a bold red circle and Bukoba town is indicated as a red square. The black romans indicate the intensity of shaking obtained from the macroseismic survey and the white circles indicate the Intensity Data Points (IDPs). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

magnitudes ranging from $M_L$ 2.7 to $M_L$ 4.1. The high values of ground response observed in Bukoba municipal (Intensity VIII) are partly a function of the strength of shaking in the most affected area, but they could also be influenced by the earthquake shaking that occurred in the heart of Bukoba town and the surrounding areas, showing differences in populations and in the level of development. This resulted in a difference of ground response indicated by the strength of shaking and damage as described in the next section focusing on different districts of the Kagera Region (Fig. 4 for district locations).

### 4.2. Intensity and duration of shaking distributions within the Kagera region

#### 4.2.1. Building typologies within the surveyed areas

The most important variables affecting earthquake damage on structures are the intensity and duration of ground shaking caused by the earthquake coupled with the quality of the engineering structures in the region. One of the factors that result in the damage to buildings during an earthquake is the type of buildings, which depends on material used, layout of the structure, height and construction method. The areas visited during the macroseismic survey in the region represent a wide range of building typologies that can be grouped based on the GEM taxonomy (Brzev et al., 2013). The GEM taxonomy, defined by various building features such as material, lateral load-resisting system, building height, etc., describes characteristic of a building or a class of buildings associated with their seismic performance. The building typologies within the areas surveyed include, but not limited to, the following types listed in Table 1, along with the corresponding taxonomic descriptions according to the GEM building taxonomy string.

#### 4.2.2. Missenyi district

Missenyi is the district where the epicenter was located. The highest intensity assigned in this area is VIII MSK-64 scale, which was reported at locations close to the epicenter in the village called Minziro (Fig. 7a). Analyzing the whole database, it can be noted that the most frequent intensity value assigned to a questionnaire was degree VI–VII. Most of the people interviewed in this area pointed out that the sensation of the earthquake was as if something heavy had been dropped, and thereafter a violent shaking of different kinds continued. Other people went even further by comparing the sound to a bomb, linking the scenario with the Kagera war of 1978. The earthquake affected the ground where some cracks were observed. The estimated duration of ground shaking was mostly between 10 and 20 s (Fig. 7b), some sites shook for 20–30 s, and a few for more than 30 s, which is likely to be associated with site effects such as variation on the geology and soil conditions.

One interesting scenario in this district was observed on two teacher's residential houses of the similar quality built next to each other at two different secondary schools. When the earthquake struck one of the two houses at each school was heavily shaken causing heavy damage, while only minor damage occurred to the adjacent house (Fig. 8a and b). The difference in the ground shaking and damage to the houses can be explained by site effects such as local geology and/or topography, resulting in both focusing and defocusing of seismic energy and amplification and de-amplification of seismic signals, as similar scenarios have been reported in many other places (Celebi, 1987, 1991; Frankel and Vidale, 1992; Gao et al., 1996).

#### 4.2.3. Bukoba municipal

The highest intensity experienced was on the scale of VIII MSK-64

**Table 1**
Building typologies within the macroseismic conducted areas in Kagera region.

| SN | Description | GEM Taxonomy description (Brzev et al., 2013) |
|---|---|---|
| 1 | Reinforced or confined masonry | MR + MOC/LWAL/FC + FC2 |
| 2 | Reinforced concrete frame without earthquake–resistant design | CR + CIP/LPB/HEX:2/RWO2/FC + FC2 |
| 3 | Unreinforced fired brick masonry | MUR + CLBRS + MOM/LWAL/RSH2 + RWO2/F99 |
| 4 | Local field stones with mud mortar | D99/MUR + STRUB + MOM/LWAL/RSH2 + RWO2/F99 |
| 5 | Adobe blocks (unbaked sundried mud block) walls | MUR + ADO + MO99/LWAL/RSH2 + RWO2/F99 |

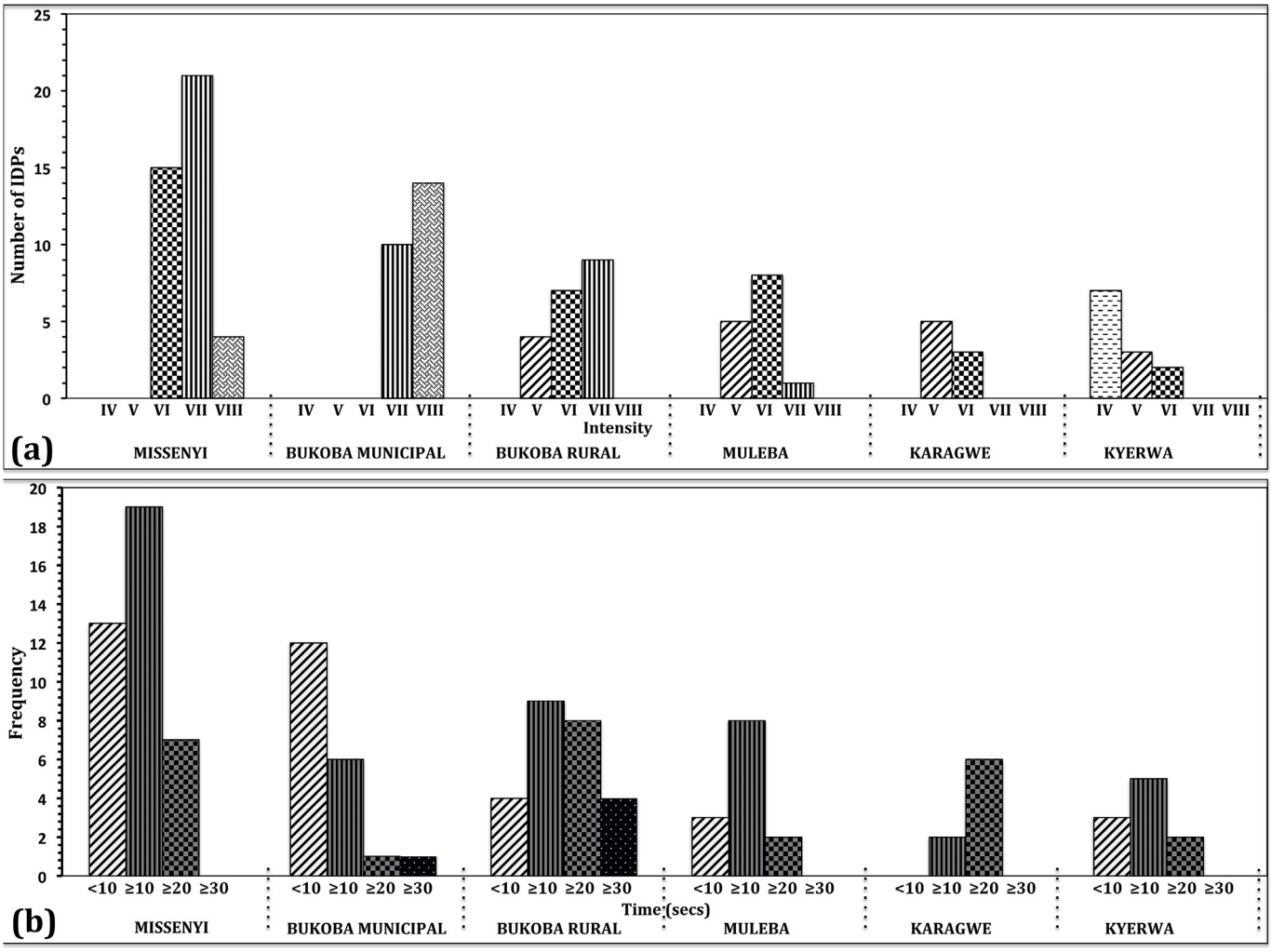



**Fig. 7.** Intensity levels and ground-shaking time in each of the six districts affected (a) Number of intensity data points (IDPs) obtained for each intensity level (b) Duration of ground shaking.

scale, which was observed quite widely over an area around Bukoba town (Fig. 7a). The VIII intensity was in general distinguished by an increased number of reports of building destruction, a greater level of fright and panic, and a greater tendency for the shaking to be described as strong. Many buildings suffered heavy damage, less damage to some buildings of moderate quality construction; total destruction of a few poor quality buildings, and some stonewalls that collapsed. In some places the shock was perceptible out of doors and many people, including some in moving cars, were disturbed. Some were not able to move. In other places, the shaking caused cracks in the ground and roads (Fig. 9). The duration of shaking in this district indicates that the most frequently reported duration of shaking was < 20 s (Fig. 7b). Few sites shook for more than 20 s, which is likely to be associated with loose sediments.

#### 4.2.4. Bukoba rural

In Bukoba rural district, 20 sites within 5 wards were surveyed. The highest intensity experienced was VII MSK-64 scale, with other intensity values of V and VI (Fig. 7a). Many inhabitants were frightened and ran out of their houses. People were stressed because the shaking was short but strong, so that most of the entire houses shook. In some cases people were unable to walk or drive cars, motorcycles and bicycles. In other cases objects overturned or fell from shelves or walls, including clocks, dishes and other glassware, some of which were broken. The intensity VII was significantly recognized by damage to buildings, which include slight to heavy damage to many buildings of good construction, and some destruction to poor buildings. The duration of shaking reported by people is mostly in the range of 10–30 s (Fig. 7b). Very few sites shook for less than 10 s and many sites shook for more than 30 s, which could be associated with site effects.

A special case was observed at one location in this district where the building suffered massive damage due to heavy and repeated vibration/shaking (Fig. 10). The person who was at the place during the instance pointed out that the dispensary building was moving up and down, back and forth for a couple of seconds (~15 s). In contrast, a building that was separated from the damaged dispensary by the width of a road experienced strong vertical motions that lasted for about 2 s, causing some minor cracks to the wall of the building. This explains the significant variation of site effects caused by change in the geology of the area where the dispensary was likely built on sandstone outcrops (lateritic sandstone).

#### 4.2.5. Muleba district

In Muleba district the highest intensity level assigned is VI on the MSK-64 scale (Fig. 7a). The macroseismic observations show that most people felt the earthquake indoors and outdoors. Many felt fear, doors were slammed, and there were clear vibrations of floors and frames in houses. In a number of cases, electrical and telephone towers swung strongly. A common report was the creaking of roofs covered with corrugated iron and falling of gable walls. In a few instances books were




**Fig. 8.** Examples of observed damage to houses in Missenyi district where two houses of similar quality, in two different locations, adjacent to each experiencing different shaking and damage (a) The shaking sustained for about 20 s (b) The houses were shaken for about 15 s.



**Fig. 9.** Example of observed cracks on the tarmac road in Bukoba town located at approximately 44 km from the epicenter.

thrown from shelves, tools from hooks and clocks thrown off the wall. Slight damage to some buildings of medium construction and moderate damage in a few buildings of poor construction was observed. Local structures built using trees sustained damage; the effect that was also observed in all other districts. The duration of ground shaking reported is mostly in the range of 10–20 s (Fig. 7b).

#### 4.2.6. Karagwe district

The intensity levels estimated for the Karagwe district are in the range of V–VI on the MSK-64 scale (Fig. 7a). A detailed macroseismic analysis from the people interviewed confirms the higher intensity of VI for this district. It was observed that many peoples felt intense shaking and many who were asleep were woken. The majority felt fear and most reported the vibration of doors and windows. Most of the ground shaking in this district was sustained for the period between 10 and 20 s, the time range that is enough to cause discomfort to people (Fig. 7b).

#### 4.2.7. Kyerwa district

The effects of the earthquake in Kyerwa district were minor as it is located far from the epicenter. The survey estimated an intensity of IV-V on the MSK-64 scale, of which large areas were dominated by intensity IV and few places experienced intensity V (Fig. 7a). In this district, light damages to buildings occurred (cracks in the plaster), with the exceptions of a few buildings with big cracks. Moreover, furniture oscillation and moving and falling of pictures and books were reported. The overall duration of shaking estimated by people was mostly in the range of 10 and 20 s (Fig. 7b).

### 4.3. Implication of site effects on the macroseismic intensity and instrumental magnitude

The overall results indicate that the intensity data points that yield the maximum intensity of VIII are mostly from Bukoba municipal and a few from the Minziro village, where most of the destruction were reported (Fig. 7a). In addition, the results show that there are also many intensity values of IV and V, in the Muleba, Karagwe and Kyerwa districts (Fig. 7a). However, the more frequently assigned intensity values are in the range of intensity VI-VII, indicating dominant intensity levels of shaking in the region (Fig. 5a). The most assigned values of intensity in the range of VI-VII are relatively high when compared with the instrumental moment magnitude, Mw5.9 of this event and as referred by other sources (Skinner and Porter, 1995, Fig. 2 and Table 2).

Most of the intensity values of VI-VII are from Missenyi and a few from Bukoba Rural districts (Fig. 7a). However, shaking of intensity level VII was also felt in a few locations far southwest of the epicenter (Muleba district), indicating patches of different intensity values that do not comply with the general trend of the isoseismal map (Fig. 6). This could be due to the amplification by local site effects that include local geology, soil conditions and/or topography. As can be referred to the geomorphology section, the Kagera region is characterized by hill ranges that are made up of resistant sandstones and the topography consists of gently undulating uplands and valleys filled with old eroded



**Fig. 10.** Examples of observed damage to houses in Bukoba rural district where the house suffered heavy and repeated vibration/shaking for about 15 s.

**Table 2**
The table showing the highest intensity expected for different earthquake magnitudes (Skinner and Porter, 1995).

| Earthquake Magnitude range | Maximum Intensity |
|---|---|
| ≥8 | XII |
| 7.4–7.9 | XI |
| 7.0–7.3 | X |
| 6.2–6.9 | VII–IX |
| 5.5–6.1 | Vi–VII |
| 4.9–5.4 | V |
| 4.3–4.8 | IV |
| 3.5–4.2 | II–III |
| ≤3.4 | I |

sediments associated with lateritic deposits in Bukoban system (Milne and Savile, 1938; Tack et al., 1984; Fernandez-Alonso et al., 2012). In terms of duration of earthquake shaking, much of the shaking time over 20 s, was observed in Bukoba Rural and Missenyi districts and a few from Bukoba municipal. This could also indicate that local site effect, suggesting a resonance effects at those sites, influenced the duration of shaking of an earthquake felt in those areas. In some sites where structures are located in soft sediments and in corrugated geomorphology, the duration of shaking was long and intense.

Both the findings of the observed high intensity values far from the epicenter and the longer duration of shaking indicate that local site effects, which result in the amplification of the seismic signals, likely played a great role on the damage (Boore, 1972; Celebi, 1987, 1991; Ashford and Sitar, 1994; Athanasopoulos et al., 1999; Faccioli et al., 2002; Midzi et al., 2015). Based on the instrumental magnitude of Mw5.9 it was anticipated that the maximum intensity would be at most VII. However, a maximum intensity of VIII was obtained in the survey, which is equivalent to the instrumental magnitude of 6.2, yielding a factor of 0.3 more than the reported Mw5.9 (Table 2). This difference is attributed to amplification due to local site effects.

## 5. Conclusions

Results from a macroseismic survey following the September 10, Kagera earthquake indicate that the isoseismal contours are elongated towards the southeast, in accordance with the rupture directivity, which is towards Bukoba town. This finding is in agreement with the orientation of the fault rupture from the focal mechanism, and the distribution of aftershocks. The more frequently assigned values of intensity ranges from VI-VII on the MSK-64 scale, with maximum intensity of VIII. Much of the duration time of shaking of over 20 s was observed in Bukoba rural and Missenyi districts, and a few from Bukoba municipal, indicating that the duration of shaking of an earthquake changes with the local geology and soil conditions due to resonance effects at those sites.

The observed variations of the intensity levels in various areas and the long duration of the earthquake shaking resulted in catastrophic damage to some structures. The catastrophic consequences of the event were on one hand attributed to the proximity of the epicenter and the poor construction quality of the residential structures, and on the other hand, to the local site effects. Site effects played a key role in the damage distribution, with sediment-induced amplification and ray focusing within the strong topographic relief being the most likely phenomena explaining the macroseismic observations. This effect is evidenced by the maximum intensity of VIII, which corresponds to the instrumental magnitude of 6.2. This result differs from the instrumental result of magnitude 5.9; the difference is attributed to amplification due to site effects such as local geology, the overburden soil and topographic features within the region.

Generally macroseismic observations on the damaged structures in several localities emphasize the importance of building reinforcement and in the future, adherence to the seismic building codes and specifications. The database of the intensity data points obtained from macroseismic survey in this study will be valuable for use in the development of the seismic intensity prediction equation for the earthquakes within the region and the East African Rift system (EARS). The database will also be valuable for the assessment of regional seismic hazard for the whole of the EARS by providing information that will help in the selection of appropriate ground-motion prediction equations.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafrearsci.2019.103568.

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