Pergamon

Journal of African Earth Sciences, Vol. 24, No. 1/2, pp. 183-195, 1997

PII: S0899-5362(97)00035-3
0899-5362/97 $17.00 + 0.00

Seismic hazards in Uganda

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Abstract—A probability seismic hazard map of Uganda is presented, based on instrumentally-derived data. The Uganda catalogue, compiled by Twesigomwe for the period 1900 to 1991, has been used. The magnitudes in the catalogue have been homogenised to surface wave magnitude (Ms); the conversion of body wave magnitude (m_b) and local magnitude (M_L) to Ms were carried out where necessary using formulae derived for the Ugandan earthquakes.

Based on seismicity and tectonics, the region was divided into 13 seismic source areas, each of which contributes to the seismic hazard throughout Uganda according to its specific seismicity. The uncertainties in the input parameters were accounted for by using a logic tree approach. On the logic tree, each uncertain parameter is represented by a node and branches emanating from that node represent alternative values on that parameter value and their assigned likelihood of being correct. Due to a lack of strong motion data, a semi-theoretical approach was used to develop an attenuation relation for the region.

The mean peak ground acceleration (PGA), which is exceeded on average once every 50 years, was calculated. The resulting hazard map suggests that the whole of Uganda except in or close to the rifts, can expect to experience a PGA of between 0.5 and 0.6 m s^{-2}, equivalent to an earthquake of intensity V-VI (slight damage) on average once every 50 years. In or close to the Western Rift, the expected PGA is between 1.0 and 2.2 m s^{-2}, equivalent to an earthquake of intensity VII-VIII (moderate to heavy damage) on average once every 50 years.

The frequency of occurrence of a PGA = 2.0 m s^{-2} (heavy damage earthquake) for various parts of Uganda was also calculated. The results indicate that northeast Uganda can expect a destructive earthquake on average once in more than 3000 years, while south of latitude 0.5°N, except in and close to the Western Rift, can expect a destructive earthquake on average once every ~1000-1500 years. In or close to the Western Rift the return period for destructive earthquake is on average less than about 50 years. © *1997 Elsevier Science Limited.*

Résumé—Une carte probabiliste de l'aléa sismique en Ouganda, obtenu par mesures instrumentales, est présentée. Pour la période 1900 à 1991, le catalogue de l'Ouganda compilé par Twesigomwe a été utilisé. Les magnitudes y ont été homogénéisées en magnitudes des ondes de surface (Ms). Lorsque nécessaires, les conversions de magnitude d'onde de volume (m_b) et de magnitude locale M_L en Ms ont été réalisées à l'aide de formules dérivées des séismes ougandais.

Sur base de la sismicité et de la tectonique, le pays a été subdivisé en treize régions, chacune contribuant en fonction de sa sismicité propre à l'aléa sismique en Ouganda. Les facteurs d'erreur des paramètres envisagés ont été pris en compte par l'application d'une approche arborescente logique. Suivant ce concept, chaque paramètre est représenté par un noeud et les branches, qui en émanent, correspondent à des valeurs alternatives du paramètre et à son niveau d'exactitude envisagé. Par manque de données sur des mouvements importants, une approche semi-théorique a été utilisée permettant le développement d'une relation d'atténuation pour la région.

La valeur moyenne de l'accélération maximale du sol (AMS), qui en moyenne n'est dépassée qu'une fois tous les 50 ans, a été calculée pour des sites rocheux. La carte de l'aléa ainsi produite suggère que l'ensemble de l'Ouganda, à l'exception

des rifts et de leur voisinage, peut s'attendre à une AMS de 0.5 à 0.6 m s^{-2}, correspondant à un séisme d'intensité V-VI (dégats faibles), en moyenne une fois tous les 50 ans. Pour un même laps de temps, la AMS escomptée dans le Western Rift ou à son voisinage est de 1.0 à 2.2 m s^{-2}, correspondant à un séisme d'intensité VII-VIII (dégats moyens à élevés).
La probabilité d'occurrence d'une AMS = 2.0 m s^{-2} (séisme à dégats élevés) pour différentes régions de l'Ouganda a également été calculée. Les résultats indiquent que le nord-est de l'Ouganda peut s'attendre à un séisme destructeur en moyenne une fois sur plus de 3000 ans tandis qu'au sud de la latitude 0.5°N, hormis le Western Rift ou son voisinage, le laps de temps est de 1000 à environ 1500 ans. Dans le Western Rift ou à son voisinage, la période escomptée pour l'apparition d'un nouveau séisme destructeur est en moyenne inférieure à environ 50 ans.

(Received 22 September 1996: revised version received 1 October 1996)

INTRODUCTION

Uganda is situated between two seismically active branches of the East African Rift System; the Western Rift (stretching from Aswa Fault Zone in the north to Lake Tanganyika in the south), and the Eastern Rift (stretching from Lake Turkana in the north to Lake Eyasi in the south; Fig.1).

Most parts of the country are therefore exposed to seismic hazards of varying degrees. Damaging earthquakes have occurred in Uganda this century. They include the Masaka earthquake of the 18 March 1945 (surface wave magnitude [Ms] = 6.0) in which 5 people were killed (Bisset, 1945; Loupekine, 1966; Maasha, 1975b), the Tooro earthquake of 20 March 1966 (Ms = 6.6) in which 160 people were killed (Loupekine, 1966) and, most recently, the Kisomoro earthquake of 5 February 1994 (Ms = 6.0) in which 8 people were killed (National Earthquake Disaster Committee, 1994). These events are listed as 18, 35 and 55, respectively, in the Appendix. Overall, the death toll in Uganda is less than one might expect with the existing quality of buildings. One of the main reasons for this fact is the light weight roofs of the buildings. Freeth (1992) also noted that the low death toll in West Africa was partly due to the light style of construction of houses. The damaging earthquakes have occurred in areas where most of the structures are wattle-and-daub buildings with grass thatch or galvanised iron sheet roofs. These type of buildings are spread throughout the country. A second class of buildings are adobe with mud mortar, and roofed with galvanised iron sheets. These are mainly old government buildings found in most administrative centres. A third class are those buildings whose walls consist of baked bricks held together with cement and roofed with galvanised iron sheets or tiles. They are usually one storey and generally common in urban centres. Most of the schools, hospitals and shops belong to this third category. Shop buildings consist of either two gable walls or poorly supported parapet walls, while the school buildings usually consist of a single storey building with two gable walls and the classrooms are separated by interior gable walls. These buildings have little resistance to horizontal forces and are therefore highly vulnerable to earthquakes. Fortunately, the last two damaging earthquakes occurred at night when the public buildings were empty, thus minimizing the death toll. The last category are buildings made of baked bricks or concrete blocks as load bearing walls with foundations, a column/beam framework and footings. They are roofed with iron sheets, tiles or have flat roofs. These include multi-storey buildings, bungalows and stores. They are commonly found in major towns like Entebbe, Kampala and Jinja. Buildings roofed with tiles, which are increasing in number at a fast rate, are likely to be more dangerous than those roofed with galvanised iron sheets in the event of an earthquake since they are heavy. Heavy buildings induce larger earthquake forces than light weight buildings.

Vulnerability to earthquakes is steadily increasing as urbanization and industrial development occupy earthquake prone areas. Thus, there is need to evaluate seismic hazards in Uganda so as to limit earthquake damage and losses. Previous seismic hazard studies in Uganda were for specific sites for hydroelectric projects (Norconsult, 1984; Sir Alexander Gibbs & Partners and Kennedy & Donkin, 1986; ACRES, 1990). The purpose of this study is to assess regional seismic hazards in Uganda as a preliminary step towards seismic risk reduction.

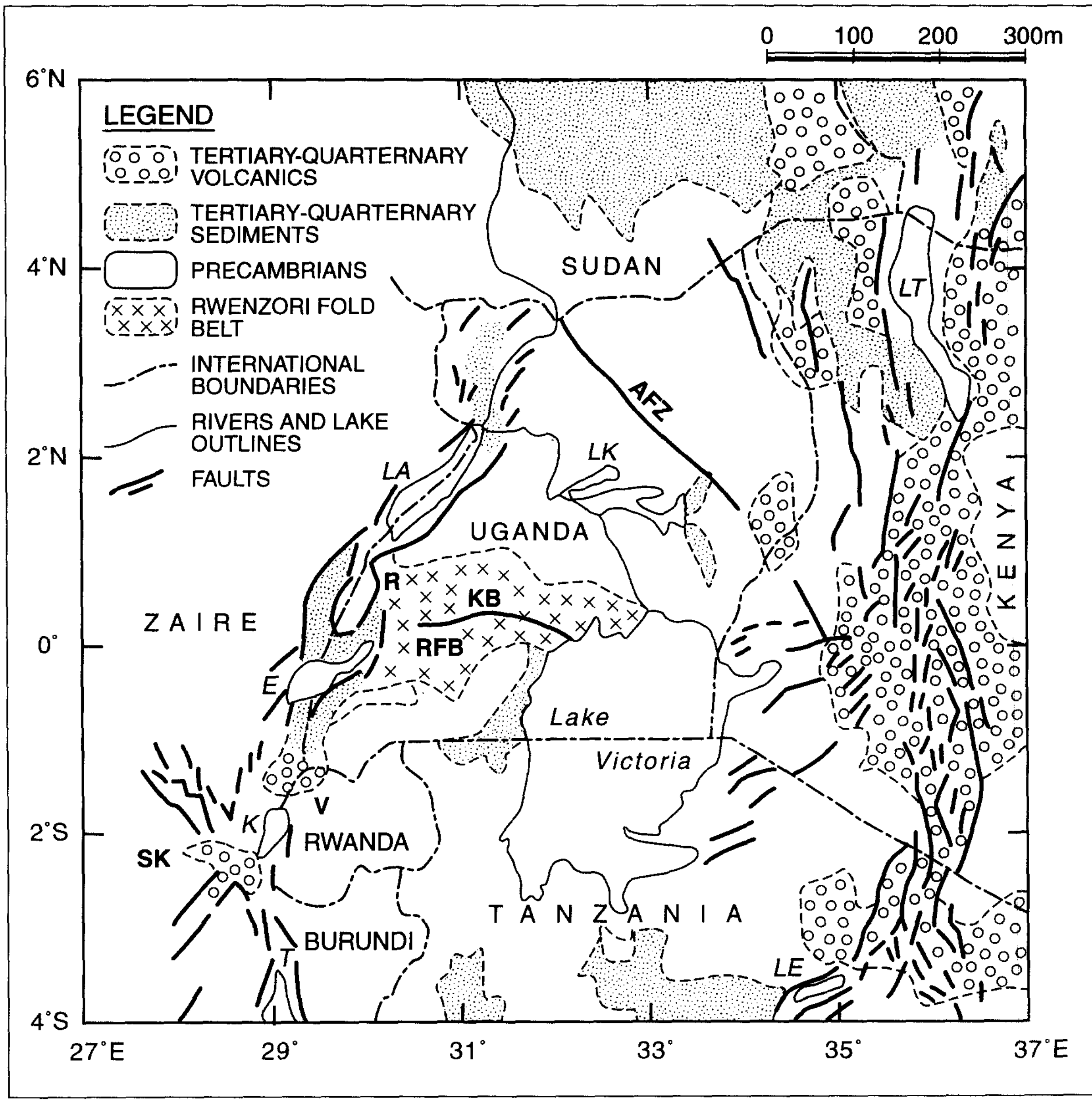

Figure 1. Generalised geology map of the study area. AFZ = Aswa Fault Zone; LK = Lake Kyoga; LA = Lake Albert; R = Rwenzori Mountains; KB = Katonga break; RFB = Rwenzori Fold Belt; E = Lake Edward; K = Lake Kivu; V = Virunga volcanic field; SK = South Kivu volcanic field; T = Lake Tanganyika; LE = Lake Eyasi; LT = Lake Turkana.

METHODOLOGY

In this paper a probability approach, initially proposed by Cornell (1968) and improved by McGuire (1978), is used to calculate seismic hazard values in Uganda. The main elements in seismic hazard analysis comprise an earthquake wave attenuation model and models of seismic sources characterised in terms of parameters deduced from geophysical, geological and seismological data.

The probability that a ground motion level is exceeded at a site in unit time is expressed as:

$$P(Z>z) = 1 - e^{-v(z)}, \qquad (1)$$

where v(z) is the mean number of events per unit time in which Z exceeds z. Z is the ground motion produced by an earthquake of magnitude M_i at source-site distance R_i with the generalised form (Reiter, 1990):

$$\ln Z = c_1 + c_2 M_i + c_3 \ln R_j + c_4 R_j + \ln(\varepsilon), \qquad (2)$$

where c_1, c_2, c_3 and c_4 are empirically determined constants and ε is a normally distributed error term with an expectance of zero and standard deviation σ.

The seismic recurrence rate for a given source is modelled by the Gutenberg-Richter relation:

$$\log N(M) = a - bM \tag{3}$$

where N(M) is the number of earthquakes per year with magnitude equal to or greater than M, and a and b are constants characteristic of the seismic source zone. The constant b (commonly known as the *b*-value) indicates the relative number of large and small earthquakes. A low *b*-value would imply a relatively higher proportion of large earthquakes than a higher *b*-value. In seismic hazard analysis, the magnitudes are restricted in the range $M_t \leq M \leq Mu$, and equation 3 is assumed valid only within this range. The modified truncated version of this relation (Reiter, 1990; McGuire, 1993) is:

$$N(M) = N(M_t)\frac{\exp(-\beta(M - \mathrm{Mu})) - \exp(-\beta(\mathrm{Mu} - M_t))}{1 - \exp(-\beta(\mathrm{Mu} - M_t))},$$

$$M_t \leq M \leq \mathrm{Mu} \tag{4}$$

where $N(M_t)$ is the number of earthquakes per year of magnitude greater than M_t and $\beta = 2.302b$. Thus, the computed seismic hazard values depend on the attenuation model described by equation (2), earthquake rates and the distribution of magnitudes for each source area. Because of inherent uncertainties and incomplete data, these parameters cannot be estimated with certainty. Uncertainties in the model parameters are accounted for by using a logic tree (Coppersmith and Youngs, 1986) to represent contributions of possible values of each parameter. A logic tree is a decision flow path consisting of nodes and branches. The model parameters are regarded as random variables whose alternative values are assigned weights reflecting their likelihood. Each branch emanating from a node represents a discrete choice of a parameter and is assigned a likelihood of being correct. The nodes are the connecting points between the input elements as determined by the general logical progression of assumptions and specifics that may be required as a result of a particular branch. Consideration of the complete set of tree branches allows the probability distribution of $v_n(z)$ in equation (1), for the nth source, to be calculated.

THE UGANDA CATALOGUE

The Uganda earthquake catalogue (Twesigomwe, *in prep.*) for the period 1850-1991 and covering an area from 4°S-6°N to 27-37°E (Fig. 1) is used in this study. The region extends into the areas surrounding Uganda. This is necessary so that earthquakes occurring outside Uganda that contribute to seismic hazards in Uganda are included. The catalogue is based on instrumental data compiled from international organizations with global databases and from individual studies. These include: the International Seismological Centre (ISC), the Preliminary Determination of Epicentres (PDE) of the US Geological Survey, Ambraseys and Adams (1986, 1992), Ambraseys (1991), Maasha (1975b), Sykes and Landisman (1964), Shah (1986) and Wohlenberg (1968). The ISC database contains data by Gutenberg and Richter, the International Seismological Summary and from the Bulawayo (BUL) seismic network in Zimbabwe. Wohlenberg's (1968) data is from the Lwiro (LWI) seismic network in eastern Zaire.

In merging the data, the following priority levels were used:

i) ISC locations followed by PDE locations were preferred to other agencies. Usually the number of stations used in the solution determines the quality of the solution. For this region, the ISC typically used many more stations than the PDE or any other agency.

ii) The locations of Ambraseys were preferred to those of the other remaining sources because the epicentres were re-determined using macroseismic information supplemented by the re-examination of instrumental reports (Ambraseys and Adams, 1986).

iii) Other sources were given priorities in the order of Sykes (re-determined epicentres for some of Lwiro's data), Gutenberg, Lwiro, Bulawayo, Maasha and Shah. The epicentres of the historical earthquakes in Shah's catalogue have very large uncertainties since earthquakes felt from the same area were assigned a common epicentre.

In addition, most of the events were not assigned magnitudes (Shah, 1986). Those events are therefore not included in this study. Solutions of some of the agencies were difficult to assess because the number of stations is not indicated. Their internal priorities are less important because there is not much overlap.

Magnitude scales used in the source data were surface wave magnitude (Ms), body wave magnitude (m_b) and local magnitude (M_L). To have a catalogue with uniform magnitude scale, all magnitudes were converted to surface wave magnitude since it saturates at a higher level than the body wave magnitude (Reiter, 1990). Thus, when surface wave magnitude (Ms) was not available directly, it was derived from m_b or from M_L, in that order of priority. The following relations obtained by the maximum likelihood regression method of Ericsson (1971), which minimises the influence of errors on both variables, was used:

$$m_b(ISC) = (0.98 \pm 0.06)m_b(PDE) + 0.29 \pm 0.07 \quad (5a)$$

$$Ms = (2.04 \pm 0.08)m_b - 5.72 \pm 0.45 \quad (5b)$$

$$Ms = (0.79 \pm 0.04)M_L(LWI) + 0.52 \pm 0.24 \quad (5c)$$

$$Ms = (1.89 \pm 0.49)M_L(BUL) - 3.86 \pm 1.9 \quad (5d)$$

Equation (5a) indicates that the body wave magnitudes by ISC (m_b[ISC]) and those by PDE (m_b[PDE]) are very close. It was therefore assumed that m_b(ISC) = m_b(PDE) for the Uganda catalogue. Equation (5b) was therefore used to convert m_b values reported by ISC and PDE to Ms values. The Bulawayo data set shows a large scatter about the regression line of equation (5d). Thus, equation (5d) is a poor predictor of Ms values given the M_L(BUL) values. Because of this large scatter, the Bulawayo data were not used in this study. Events from some of the agencies had no multiple magnitudes. It was, therefore, not possible to carry out regression analysis. These were not converted to unified magnitude Ms.

In hazard analysis, a Poisson model of earthquake occurrence is commonly used (Kulkani *et al.*, 1984; Bender and Perkins, 1987). In such a model, the probability of ground motions is based on independent events and not on time series or time-dependent events, such as aftershocks. Thus, a sub-catalogue which excluded aftershocks, earthquake swarms and the Bulawayo data was prepared. An event was considered an aftershock if it occurred within 365 days after the main shock and its epicentre was within the radius of 0.5° of the main event. From the point of view of seismic hazards, the most important events are the large magnitude earthquakes, therefore events with Ms≤4.0 are also excluded from the sub-catalogue. Ms = 4.0 was selected as the threshold or lower bound magnitude on the basis that shallow earthquakes down to that magnitude could damage poorly designed or non engineered structures in Uganda. The sub-catalogue contains 263 events. Earthquakes of magnitude Ms≥5.0 in the sub-catalogue are listed in the Appendix. Figure 2 shows the distribution of the earthquakes in the sub-catalogue in magnitude-time space. The period before 1900 is not included in Fig. 2 since there are only two reported events with estimated magnitude in 1850 and 1857. As can be seen from Fig. 2, reporting is not uniform for the entire length of the sub-catalogue. There are more events for the period 1957-1971 than any other period for lower magnitudes 4.0-4.5. This peak is due to the contribution from theLwiro seismic network, whose data is not available to the author for the period after 1971.

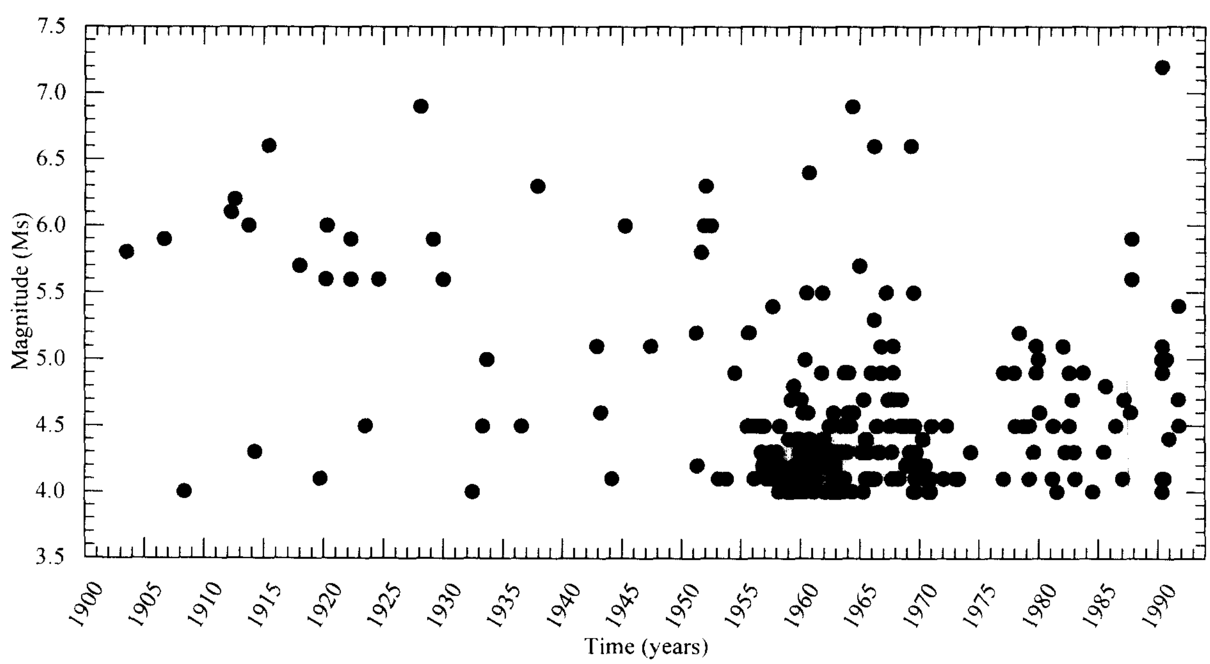

Figure 2. *Time-magnitude plot for the time interval 1900 to 1991 for earthquakes used in this study. All magnitudes are on the surface wave scale with a threshold magnitude of Ms = 4.0.*

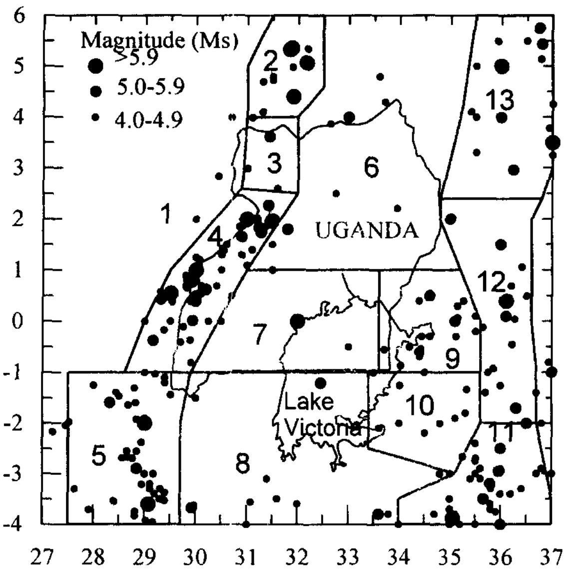

Figure 3. Epicentres in the Uganda earthquake sub-catalogue, for the time period 1900-1991, used in seismic hazard analysis. All magnitudes are on the surface wave scale with a threshold magnitude of Ms = 4.0. The seismic source areas 1-13, used to estimate the probability of seismic hazards in Uganda, are marked as polygons.

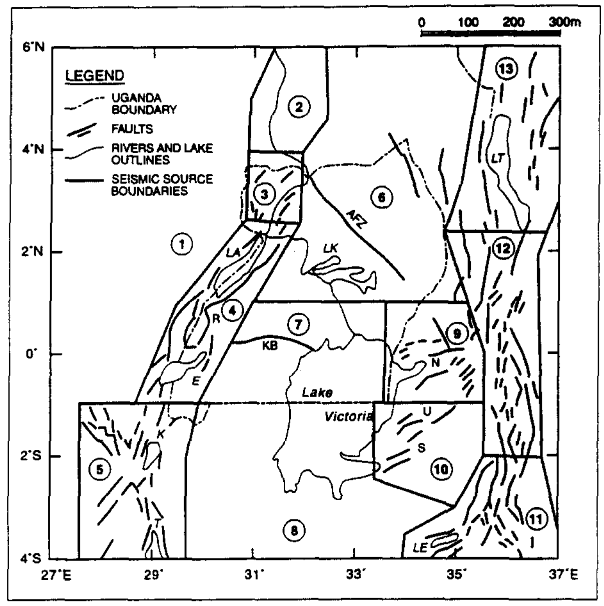

Figure 4. Main faults and seismic zones used in this study. The seismic source areas 1-13 are indicated by polygons. AFZ = Aswa Fault Zone, LK = Lake Kyoga, LA = Lake Albert, R = Rwenzori Mountains, KB = Katonga break, E = Lake Edward, K = Lake Kivu, T = Lake Tanganyika, LE = Lake Eyasi, LT = Lake Turkana, U = Utimbere Rift, S = Speke Gulf Rift, N = Nyanza Rift.

SEISMIC SOURCE ZONES

The present approach to seismic hazard analysis requires the zonation of seismicity into seismic source zones. Although most earthquakes are caused by faulting, it is not possible to identify individual earthquake generating faults precisely enough for use in seismic hazard analysis in Uganda. This is due to the scarcity of seismographs in the region as well as a limited knowledge of the geotectonics of the region. Generally, research in the area has focused on mineral resources. Since the seismicity cannot be related to specific faults, the locations of possible earthquakes are represented by area sources.

The seismicity of Uganda and adjacent areas is modelled by 13 seismic source zones based on seismic, geological and tectonic considerations. The geographical boundaries of the zones are shown in Figs 3 and 4, superimposed on seismicity and the tectonic maps. The following guiding principles have been used in the zonation:

i) each source zone should have reasonably uniform seismicity. It is assumed that each point within a source zone has the same probability of being the epicentre of a future earthquake since a Poisson model is assumed in this study; and

ii) the zonation should be consistent with the regional geology and tectonics.

Zones have been defined as polygons to satisfy the input requirements to the hazard computer program. It can be seen from Figs 3 and 4 that the zonation follows the major regional geological features, as well as the seismicity. Zones 2 to 5 represent the Western Rift; 11 to 13 the Eastern Rift; 7 the Rwenzori Fold Belt; 10 the Speke and Utimbere Rift units; 9 the Nyanza Rift; and 1, 6 and 8 the Zaire-Uganda-Tanzania Precambrian basement (craton).

Seismic source zone 2 is dominated by relatively strong earthquakes, but with a poorly understood tectonic control. Therefore, the source zone boundary adopted for zone 2 is based purely on the seismicity and is not controlled by geological or geophysical features. Zone 3 is a part of the rift striking in a north-south direction, unlike the southern part and its boundary, which is defined by a series of *en enchelon* faults. Zone 4 includes the Rwenzori Mountain block (Fig. 4), which is bounded by steeply dipping, seismically active normal faults (Maasha, 1975a; Ebinger, 1989). The northern segment is defined by a node between the north-northeast - south-southwest trending Lake Albert Basin, the north-south trending Nile Rift (zone 3) and the east-west trending River Nile. The southern part is marked by the Virunga volcanic mountains (Figs 1 and 4). The Virunga Mountains are associated with eight main

Table 1. Number of earthquakes in each seismic zone used to calculate *b*-values for the four gross seismic sources

Region	zone	4.2	4.7	5.2	5.7	6.2	6.7	7.2	Total	Mmax	b-value	T (yrs)
Western	2	0	4	0	0	1	1	2	8	7.2		for Ms6.0
rift	3	1	1	0	1	0	0	0	3	5.5	0.79	18
gross	4	22	10	8	5	3	2	0	50	6.6		
source	5	11	19	2	0	2	0	0	34	6.4		
Total		34	34	10	6	6	3	2	95			
Craton	1	1	2	0	0	0	0	0	3	4.7		
gross	6	2	4	1	0	0	0	0	7	5.9	1.17	240
source	8	8	1	1	1	0	0	0	11	5.8		
Total		11	7	2	1	0	0	0	21			
Rwenzori	7	2	2	0	0	1	0	0	4	6.0		
fold gross	9	5	8	2	0	0	0	0	15	5.4	1.26	250
source	10	13	1	0	0	0	0	0	14	4.6		
Total		20	10	2	0	1	0	0	33			
Eastern	11	22	8	3	2	1	1	0	37	6.9		
rift gross	12	3	4	3	2	0	0	0	13	6.9	0.88	35
source	13	6	3	1	3	2	0	0	15	6.3		
Total		31	15	7	7	3	2	0	65			

Magnitude intervals are centred around values 4.2, 4.7, 5.2, 5.7, 6.2, 6.7 and 7.2. Mmax is the maximum reported magnitude in each zone. T is the return time for Ms = 6.0.

volcanoes aligned along a fracture zone transverse to the rift axis (Kampunzu *et al.*, 1986). Zone 5 is formulated to reflect the distribution of faulting and volcanism in this part of the Western Rift. Some of the faults branch off northwestwards and southwestwards, unlike the north-northeast striking normal faults of the rift valley. Zone 7 represents the Rwenzori Fold Belt with its associated Katonga break (Figs 1 and 4). Tertiary and Quaternary faults striking mainly parallel to the Katonga Fault break occur in this region (Atlas of Uganda, 1969; Maasha, 1975b). The area is modelled as a broad zone capable of producing relatively strong earthquakes, as attested by the Masaka earthquake of 1945 (event 18 in the Appendix; Ms = 6.0). The Utimbere and Speke Gulf Rift units have been modelled as one zone. The boundaries between zones 7, 9 and 10 are based on seismicity. Zone 11 is characterised by splay faults, which produce a pattern of block faulting and tilting. It is the most seismically active section of the Eastern Rift. Zone 12 is the main part of the Eastern Rift. It is bounded by major faults. The rift floor is characterised by extensive grid faulting and recent volcanic and geothermal activity (Baker *et al.*, 1972) (Fig. 1). Zone 13 lies within a broad depression between the Kenyan and Ethiopian domes. It is regarded as a diffuse zone of faulting linking the north and south segments of the Eastern Rift. Zones 1, 6 and 8 are part of stable cratons. The Uganda Craton (Fig. 1) is intersected by the Precambrian Aswa Shear Zone, which seems to be seismically stable.

SEISMIC SOURCE PARAMETERS

Seismic sources are modelled with the parameters reflecting the characteristics of each source. The parameters include the *b*-value (which indicates the relative number of large and small earthquakes), annual activity rate, maximum magnitude and focal depth. These parameters are determined as follows.

b-values and activity rates

In order to have reliable *b*-values on a zone by zone basis, a minimum number of earthquakes is needed. According to Bender (1983), at least 25 earthquakes are required to obtain an estimate of *b* with a standard deviation as low as ~0.25*b*. Zone totals of this number are very few in the study area, as can be seen from Table 1. However, the *b*-value is expected to be the same for areas of the same tectonic settings, although the activity rate parameter is liable to vary from one seismic source to another. Consequently, zones of similar tectonic settings are combined to form a gross source: Zones 2

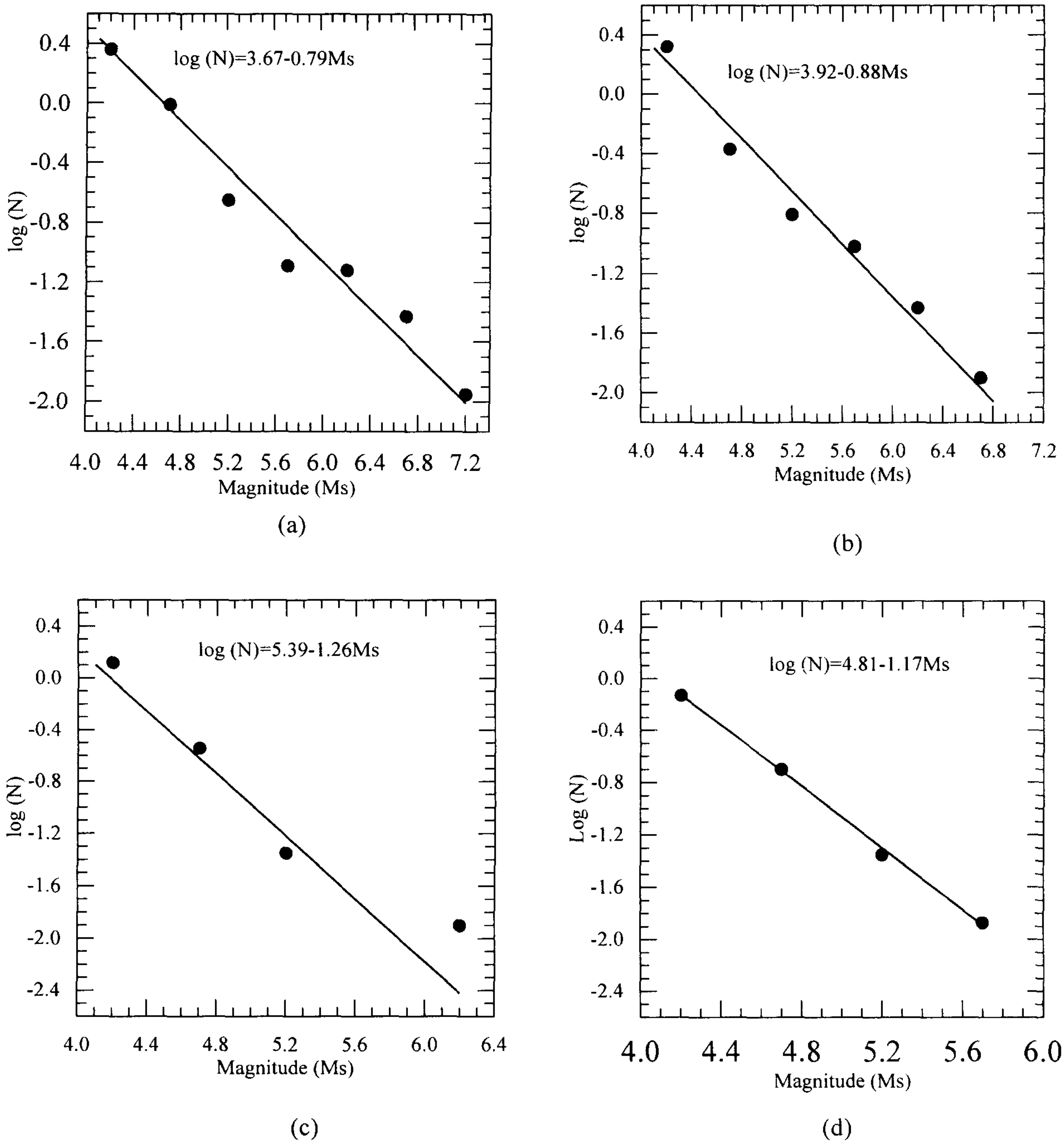

Figure 5. *Number of earthquakes in an interval versus magnitude for the four gross seismic sources used in seismic hazard analysis. The straight lines are the maximum likelihood fit to the data (Weichert, 1980) and the corresponding equations are also indicated on the plots. The magnitude intervals are centred around the values 4.2, 4.7, 5.2, 5.7, 6.2, 6.7 and 7.2. (a) The combined sources (zones 2, 3, 4 and 5) which constitute the Western Rift region. (b) Zones 11, 12 and 13 which constitute the Eastern Rift region. (c) Zones 7, 9 and 10 which constitute the Rwenzori Fold Belt region. (d) Zones 1, 6 and 8 which constitute the craton region.*

to 5 constitute a gross source zone representing the Western Rift. Although zone 2 may not be a part of the Western Rift, it is included in it since it does not fit in any of the other gross zones and seems to be similar, in terms of the seismic activity, to the Western Rift. Since it has been suggested that the faults within the Rwenzori Fold Belt may continue across Lake Victoria to the Nyanza and Speke Gulf rift units (Maasha, 1975b; Rach and Rosendahl, 1989), zones 7, 9 and 10 are combined to form the Rwenzori Fold Belt gross zone. Zones 11 to 13 constitute a gross zone representing the Eastern Rift and the Precambrian basement zones 1, 6 and 8 form a fourth gross zone.

Table 2. Input parameters used in calculating the peak ground acceleration

zone	b-value			activity rate, N		Mu		focal depth (km)		
no.	L	C	U	C	U	C	U	L	C	U
1	1.12	1.17	1.22	0.142	0.185	5.9	6.4	5.0	15.0	25.0
2	0.74	0.79	0.84	0.311	0.404	7.2	7.7	5.0	15.0	25.0
3	0.74	0.79	0.84	0.133	0.173	7.2	7.7	5.0	15.0	25.0
4	0.74	0.79	0.84	1.881	2.445	7.2	7.7	5.0	15.0	25.0
5	0.74	0.79	0.84	1.271	1.652	7.2	7.7	5.0	15.0	25.0
6	1.12	1.17	1.22	0.332	0.432	5.9	6.4	5.0	15.0	25.0
7	1.21	1.26	1.31	0.217	0.282	6.0	6.5	5.0	15.0	25.0
8	1.12	1.17	1.22	0.521	0.677	5.9	6.4	5.0	15.0	25.0
9	1.21	1.26	1.31	0.746	0.970	6.0	6.5	5.0	15.0	25.0
10	1.21	1.26	1.31	0.697	0.906	6.0	6.5	5.0	15.0	25.0
11	0.83	0.88	0.93	1.470	1.911	6.9	7.4	5.0	12.5	25.0
12	0.83	0.88	0.93	0.521	0.677	6.9	7.4	5.0	12.5	25.0
13	0.83	0.88	0.93	0.601	0.781	6.9	7.4	5.0	12.5	25.0
wt	0.20	0.60	0.20	0.70	0.30	0.7	0.3	0.25	0.5	0.25

Mu = expected maximum magnitude; L, C and U are the lower limit, calculated or centre value and upper limit, respectively, of the input parameter; wt = weight assigned to values in the same column.

Assuming an uncertainty in magnitude of ±0.5, the earthquakes are grouped into magnitude classes of 4.0-4.4, 4.5-4.9, 5.0-5.4, 5.5-5.9, 6.0-6.4, 6.5-6.9 and 7.0-7.4. Figure 2 is then used to determine the period in which each magnitude class is completely reported. The sub-catalogue can be considered complete for magnitude classes 4.0-4.4 for the period 1957-1971, 4.5-4.9 for the period 1957-1991, 5.0-5.4 for the period1947-1991 and 5.5-5.9 for the period 1918-1991. For Ms≥6.0 the events are completely reported for the entire period of 90 years. The *b*-values and annual occurrence rates for the gross sources were determined using the maximum likelihood procedure of Weichert (1980). The method takes into account different completeness times for different magnitude classes, thus using most of the data. The number of earthquakes which were used to calculate the *b*-value and activity rate for the source zones is listed in Table 1. The results obtained are summarised in Table 2. Magnitude recurrence relations for the gross source zones are shown in Fig. 5. Based on the annual occurrence rate, the average recurrence times for magnitude class Ms = 6.0-6.4 were calculated and are shown in Table 1.

The calculated *b*-value for the gross source is imposed on each of the constituent zones within the gross zone and values of N(M) in equation (4) are calculated as follows:

i) the zone contribution to the gross zone equals the total number of events observed within the constituent zone divided by the total number of events observed within the gross zone;

ii) the magnitude class contribution to a zone equals the zone contribution to the gross zone multiplied by the total number of events within the magnitude class;

iii) N_{zone} (Ms = 4.0) equals the sum of all events in step (ii) above.

Values of N were tied to the lower bound magnitude Ms = 4.0 as mentioned earlier. The results are summarised in Table 2. In modelling the activity rate (N), a variability of +30% is allowed to account for the earthquakes, like those reported by Bulawayo, which were not included in this study. The corresponding values of *N* are given weights of 0.3 each, while the calculated value in step (iii) above is assigned a weight of 0.7.

Maximum magnitudes

The maximum magnitude (Mu) in equation (4) is difficult to assess in any given area. In the case of Uganda, information about fault lengths or the slip and displacement of palaeoseismic events, generally used in other areas, is lacking. Since constituent zones in a gross source are assumed to have a similar geological setting, it is possible that any of these zones may be the source of the upper bound magnitude Mu earthquake. Consequently, as a conservative estimate, the maximum reported earthquake in the gross zone is taken as the lower limit to the upper bound earthquake for the constituent zones. This value is assigned a 0.7 probability. Since it happened in the past, it is certainly possible that it can happen in the future. A 0.5 magnitude unit is added to the observed maximum magnitude in the gross source to obtain an alternative value in the logic tree. This would be justified if the recurrence time interval of the expected maximum earthquake is longer than the time span of the catalogue. This value is assigned a 0.3 probability.

Focal depths

The focal depths of earthquakes are poorly known due to the scarcity of data. However, microearthquake studies indicate that focal depths are generally shallow (<25 km). Examples are: Rykounov *et al.* (1972): focal depth of5-20 km, zone 4; Maasha (1975a): generally 0-20 km, Rwenzori area; Tanaka (1983): 8-16 km, Virunga area; Bungum and Nnkono (1984): majority are 18-20 km, Stiegler's George, Tanzania; Tongue *et al.* (1994): generally below 12 km, Gregory Rift. From the modelling of seismic waves, Shudofsky (1985) found the focal depths to be generally 7-29 km down, in East Africa. The values in Table 2 are based on the above results. The centre values in the Table 2 were assigned weights of 0.5, while extreme values were assigned weights of 0.25 each.

Attenuation relation

Due to a lack of strong motion data for Uganda and adjacent areas, a semi-theoretical technique was used to develop the attenuation relation of equation (2). The constant c_4 in equation (2) may be expressed as:

$$c_4 = \frac{-\pi f}{\beta Q(f)}, \quad (6)$$

where f is the frequency, β is the Lg wave velocity, here taken as 3.5 km s^{-1} and Q(f) is the seismic quality factor, which may be written as:

$$Q(f) = Q_0 f^{\eta}. \quad (7)$$

For the region under study, $Q_0 = 330$ and $\eta = 0.5$ for wave frequencies of 0.5-2 Hz (Xie and Mitchell, 1990). Substituting these values in equation (6) gives $c_4 = -0.0027$. Uganda, being situated primarily on metamorphosed Precambrian formations, probably exhibits attenuation similar to that seen in eastern Canada. Krinitzky *et al.* (1988) developed equations like (2) from a world-wide data set for eastern Canada for mean peak ground acceleration (PGA), shallow earthquakes and hard rock sites. Applying the relation to Uganda, and including the above attenuation term developed for the region, the following relation applies for this study:

$$\ln a = 2.832 + 0.886\text{Ms} - \ln R - 0.0027R + \ln(\varepsilon), \quad (8)$$

with PGA in m s^{-2}. The constant term and scaling coefficient of Ms relate to the near field excitation of the earthquake wave motion, which is considered to be more or less independent of tectonic conditions (Hanks and Johnston, 1992; Bungum *et al.*, 1992). The attenuation relationship of equation (8) is shown in Fig. 6. Krinitzky *et al.* (1988) did not determine the standard deviation (σ) of the ln(ε) in equation (8), although for intraplate areas, Dahle *et al.* (1991) found σ to be between 0.54-0.77 and Campbell (1985) gives a value of 0.55. The values of 0.5, 0.6 and 0.7 with weights 0.3, 0.4 and 0.3, respectively, are used in this study.

SEISMIC HAZARD COMPUTATION

The NPRISK computer program (NORSAR, 1994) was used to calculate the probability of the seismic hazards. The program is based on McGuire's (1976, 1978) programs EQRISK and FRISK. The program accepts alternative values of the input parameters and their likelihood of being correct. Then the program calculates the total hazard from all the sources and its uncertainty. For individual seismic sources, the input parameter variability in maximum magnitude, focal depth, *b*-value, activity rate and attenuation relationship are formulated into a logic tree. Each combination of parameters is used to calculate the seismic hazard. Thus, for each of the given ground motion amplitudes there is a distribution of hazard represented by

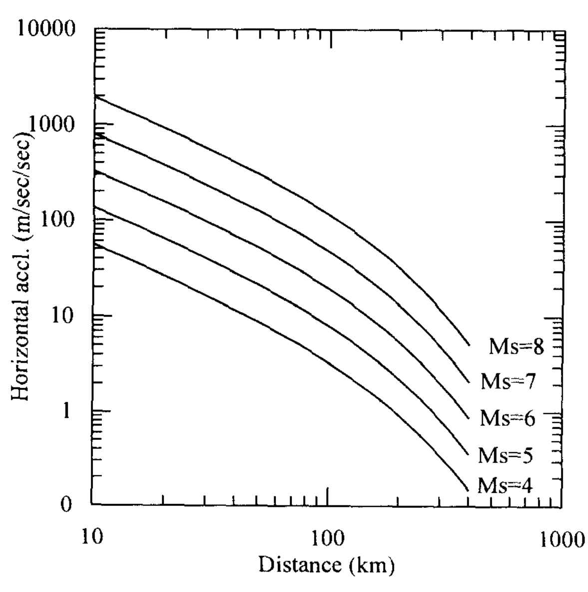

***Figure 6.** Attenuation relationship used in this study.*

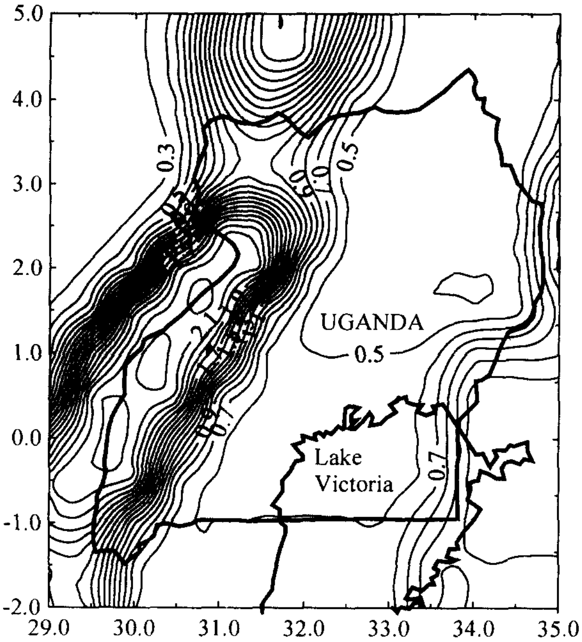

Figure 7. Mean PGA (m s^{-2}) to be exceeded on average once every 50 years.

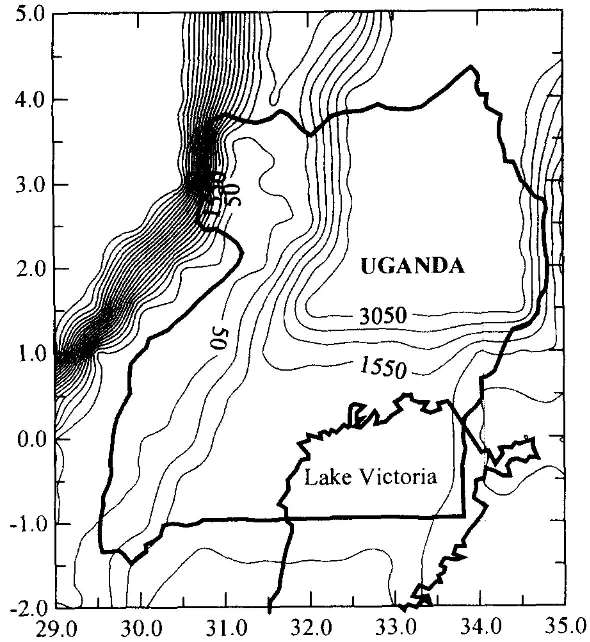

Figure 8. Map of Uganda showing the frequency in years with which various parts of the country can expect a PGA = 2 m s^{-2} (intensity VIII earthquake).

the calculated values at the end of each branch. From the hazard distribution, the program calculates the mean and median hazards, together with the hazards at given confidence levels. The input parameters, their alternative values and the weights reflecting their likelihood are listed in Table 2. The mean peak ground acceleration to be exceeded on average once every 50 years was calculated. Calculations were carried out at 441 grid points with a 0.5° spacing. Figure 7 shows the mean PGA (m s^{-2}) for different parts of Uganda. The map is valid for the largest horizontal component of ground motion at the rock sites. With the PGA fixed at 2.0 m s^{-2}, the frequency in years with which various parts of the country can expect such an earthquake was calculated. The results are shown in Fig. 8.

DISCUSSION AND CONCLUSIONS

The inputs to probability hazard studies are generally uncertain, being based on subjective judgments and the interpretation of limited data. This study is no exception. However, to account for some of these uncertainties all the relevant input parameters were regarded as random variables and their uncertainties were accounted for by using a logic tree approach, which accommodates alternative input parameter values for a range of hypotheses. The attenuation relationship used for all seismic source areas was derived for the Uganda Craton. However, the attenuation in the rifts is expected to be higher than in the craton. Therefore, the calculated mean PGA values in or close to the rifts give the maximum PGA to be expected in those areas. There is no simple direct relationship between horizontal acceleration and earthquake damage. However, to a first approximation a rate of acceleration of about 1.0 m s^{-2} is sufficient to cause moderate damage, equivalent to a Mercalli intensity of about VII (Trifunac and Brady, 1975). The resulting hazard map suggest that the whole of Uganda, except in or close to the rifts, can expect to experience a PGA of between about 0.5 and 0.6 m s^{-2} (equivalent to intensity V-VI—slight damage) once every 50 years. In or close to the Western Rift the expected PGA is between 1.0-2.2 m s^{-2} (equivalent to intensity VII-VIII—moderate to heavy damage) once every 50 years.

In or close to the Western Rift, the predicted average recurrence time intervals for Ms = 6.0-6.4 and 7.0-7.4 are ~18 and ~100 years, respectively. These numbers are generally consistent with the fact that over a time period of 90 years (from 1902 to 1991), six earthquakes within interval Ms = 6.0-6.4 have been reported and only one of Ms = 7.2. As for the Rwenzori Fold Belt, a 6.0 earthquake is expected about once every 250 years.

If a PGA of 2.0 m s^{-2} is taken as equivalent to intensity VIII (heavy damage), then most parts of northeast Uganda can expect a destructive earthquake on average once in more than 3000 years, while south of latitude 0.5°N (except in and close to the Western Rift) can expect a destructive earthquake on average once every ~1000-1500 years. In or close to the Western Rift the return period for a destructive earthquake is on average less than ~50 years.

The derivation of attenuation relationships for the prediction of earthquake ground motion requires a continuous effort and needs to be updated whenever new recorded data sets from earthquakes in the magnitude and distance ranges of engineering interest or appropriate geological environment appear. Due to a lack of strong motion data, a semi-theoretical approach has been used to develop the attenuation model for the region. There is therefore a need to acquire strong motion data within the region so as to improve the attenuation model.

ACKNOWLEDGEMENTS

The author thanks Y. Kaahwa, E. J. B. Banda, and A. Kuvvet for their helpful discussion and reviewers S. J. Freeth and Paul W. Burton, whose comments helped to significantly improve the manuscript. NORSAR provided the NPRISK computer program used to calculate PGA. This research was supported by funds from International Science programs (ISP) project UGA:01/2 and Makerere University.

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APPENDIX

List of earthquakes in each seismic source zone. Abbreviations used in the Table are:

mo, day, hr, min = month, day, hour and minute of origin time;

lat. = epicentre latitude in degrees north (positive) and south (negative);

long. = epicentre longitude in degrees east;

Ms = surface wave magnitude.

no	year	mo.	day	hr	min	lat.	long.	Ms
1	1903	06	04	14	58	2.00	35.00	5.8
2	1906	08	25	11	54	4.00	33.00	5.9
3	1912	03	08	14	45	-2.00	29.00	6.1
4	1912	07	09	08	18	2.00	31.00	6.3
5	1913	09	16	11	56	3.50	37.00	6.0
6	1915	05	21	04	18	4.40	31.90	6.6
7	1917	12	05	12	49	-2.50	36.00	5.7
8	1920	02	10	02	30	0.50	30.00	5.6
9	1920	03	21	00	28	1.00	30.00	6.0
10	1922	03	15	03	30	-4.0	36.00	5.9
11	1922	03	16	14	57	4.00	36.00	6.3
12	1924	07	01	06	20	1.50	36.00	5.6
13	1928	01	06	19	31	0.40	36.11	6.9
14	1929	02	10	03	14	0.40	30.00	5.9
15	1929	12	11	03	48	2.00	31.50	5.6
16	1937	11	30	12	57	5.00	36.00	6.3
17	1942	11	27	03	03	-2.00	36.50	5.1
18	1945	03	18	08	01	0.00	32.00	6.0
19	1947	05	17	03	47	-2.00	36.50	5.1
20	1951	03	31	08	54	0.10	36.10	5.2
21	1951	08	20	12	25	-3.80	33.60	5.8
22	1951	11	01	11	10	-4.00	35.25	6.0
23	1952	06	30	21	04	0.55	29.50	6.0
24	1955	08	14	15	29	0.50	34.60	5.2
25	1955	09	04	22	13	1.66	30.90	5.2
26	1957	09	01	16	32	0.00	35.10	5.4
27	1960	05	04	02	17	-1.21	32.46	5.0
28	1960	07	08	18	34	-1.70	36.30	5.5
29	1960	09	22	09	14	-3.19	28.98	5.4
30	1961	11	12	02	15	0.44	29.32	5.5
31	1962	03	08	21	38	3.70	28.99	5.1
32	1964	05	07	05	45	-3.88	35.06	6.9
33	1964	12	21	14	03	-3.67	29.93	5.7
34	1966	03	09	03	12	2.27	31.42	5.3
35	1966	03	20	01	42	0.81	29.90	6.6
36	1966	10	05	08	34	0.02	29.94	5.1
37	1967	03	10	12	41	0.63	30.19	5.5
38	1967	10	30	19	55	1.80	31.80	5.1
39	1969	04	22	21	59	1.96	31.49	6.6
40	1969	07	15	16	33	3.62	31.44	5.5
41	1978	05	23	09	02	2.96	36.22	5.2
42	1979	10	25	18	51	-2.89	28.83	5.1
43	1979	12	04	07	34	1.74	31.28	5.0
44	1982	01	09	17	30	-1.59	28.31	5.1
45	1987	10	25	16	46	5.44	36.80	5.9
46	1987	10	28	08	58	5.75	36.74	5.6
47	1990	04	05	19	20	-2.95	35.96	5.0
48	1990	05	15	16	24	-3.11	35.86	5.1
49	1990	05	15	15	21	-3.20	35.79	5.1
50	1990	05	20	02	22	5.07	32.16	7.2
51	1990	05	24	19	34	5.33	31.84	6.4
52	1990	05	24	20	00	5.36	31.87	7.0
53	1990	09	04	01	48	-0.37	29.16	5.0
54	1991	10	09	17	22	1.84	31.24	5.4
55	1994	02	05	23	34	0.59	30.04	6.0