Seismic hazard assessment in Eastern and Southern Africa

Vunganai Midzi (1), **Dumisani J. Hlatywayo** (2), **Lostina S. Chapola** (3), **Fekadu Kebede** (4), **Kuvvet Atakan** (5), **Daniel K. Lombe** (6), **Gadi Turyomurugyendo** (7) **and Fred Alex Tugume** (7)

(1) *Goetz Observatory, Department of Meteorology, Ascot, Bulawayo, Zimbabwe*
(2) *Applied Physics Department, Faculty of Applied Sciences, Bulawayo, Zimbabwe*
(3) *Geological Survey of Malawi, Zomba, Malawi*
(4) *Geophysical Observatory, Faculty of Sciences, Addis Ababa University, Addis Ababa, Ethiopia*
(5) *Kuvvet Atakan Institute of Solid Earth Physics, University of Bergen, Norway*
(6) *Geological Survey of Zambia, Geological Section, Lusaka, Zambia*
(7) *Department of Geological Survey and Mines, Entebbe, Uganda*

Abstract
Seismic hazard assessment for the Eastern and Southern Africa region was done using the probabilistic approach. Seismic hazard maps for 10% exceedance in 50 years, 10% exceedance in 100 years, as well as for 50 and 100 years return periods were prepared using the FRISK88M software. The area involved covers a wide region bounded by latitudes 40°S-25°N and longitudes 10°E and 55°E. Input parameters for the computations were obtained using the recent earthquake catalogue compiled by Turyomurugyendo. The catalogue which covers the time period 627-1994, contains earthquakes within the area bounded by 40°S-25°N and 10°E-55°E, with homogeneous magnitudes (M_S). Since a Poisson model of earthquake occurrence is assumed, dependent events were cleaned from the catalogue. Attenuation relations for the Eastern and Southern Africa region based on the strong motion data are virtually non-existent. However, attempts have been made recently by Jonathan and Twesigomwe to establish an average attenuation relation for the region. These relations were used in the computations. Possible uncertainties in the attenuation relations were accounted for using the logic-tree formalism. The results are presented in seismic hazard maps in terms of Peak Ground Acceleration (PGA) for the mean and the 85th percentile. The distribution of PGA values indicate relatively high hazard along the East African rift system. In the northern segments of the rift system, they exceed 250 gals for 10% probability of exceedence in 50 years.

Key words *seismic hazard assessment – African rift – earthquakes – UN/IDNDR*

1. Introduction

Eastern and Southern Africa covers a region which is prone to a significant level of seismic hazard due to the presence of the East African rift system. A number of destructive earthquakes, some causing loss to life, have been reported during this century. For example, in Eritrea, the port city of Massawa was destroyed by an earthquake which occurred in 1921. In Ethiopia, they include the 1960 Awasa earthquake (M_S = 6.1), the 1961 Kara Kore earthquake which completely destroyed the town of Majete and severely damaged Kara Kore town, the 1969 Serdo earthquake (M_S = 6.3) in which four people were killed and 24 injured, 1989 Dobi graben earthquake (M_S = 6.5) which destroyed several bridges on the highway connecting the port of Assab to Addis Ababa, the 1983 Wondo Genet and the 1985 Langano earthquakes which caused

Mailing address: Dr. Vunganai Midzi, Goetz Observatory, Department of Meteorology, P.O. Box AC 65, Ascot, Bulawayo, Zimbabwe; e-mail: goetz@harare.iafrica.com

damage in parts of the main Ethiopian rift. In Uganda, damaging earthquakes include the 18 March 1945 Masaka event (M_s = 6.0) in which five people were killed, the Tooro event of 20 March 1966 (M_s = 6.1) in which 160 people were killed, 1300 people injured and 7000 buildings were destroyed or damaged, and the Kismoro earthquake of 5 February 1994 (M_s = 6.0), which killed eight people. In Malawi, the Salima earthquake (M_s = 6.1) of 10 March 1989 killed nine people. Other damaging earthquakes have been reported in Tanzania which includes the Kasanga earthquake (M_s = 7.3) of 13 December 1910, which caused significant damage in southern Tanzania. Realising this major threat in the region, which covers an area of approximately 5.5 million square kilometres with more than 120 million people, the region's capacity in earthquake preparedness and hazard mitigation needs to be improved significantly. The prerequisite in any hazard mitigation program is to investigate the earthquake hazard potential in the region through an assessment of seismic hazard using state-of-the-art techniques. In this report, probabilistic earthquake hazard analysis is performed for the region using the latest available computer software provided by the Risk Engineering (1996), within the framework of the Global Seismic Hazard Assessment Program (GSHAP). The results are presented in terms of seismic hazard maps showing the Peak Ground Acceleration (PGA) levels covering the region for 10% probability of exceedance in 50 years, 10% exceedance in 100 years, as well as 50 and 100 years return periods.

In recent years, there has been increasing co-operation in seismology among nine countries in the Eastern and Southern Africa region. These are Eritrea, Ethiopia, Uganda, Kenya, Tanzania, Malawi, Zambia, Zimbabwe and South Africa. This co-operation has lead to the establishment of the Eastern and Southern Africa Regional Seismology Working Group (ESARSWG), which is now a recognised component of the Committee for Developing Countries under the International Association of Seismology and Physics of the Earth's Interior (IASPEI). One of the major tasks of the ESARSWG is to improve the understanding of seismic activity and assess the seismic hazard potential of the Eastern and Southern Africa region. Since the establishment of EASRSWG, three workshops have been held specifically on seismic hazard assessment. The first preparatory meeting was held in Kampala, Uganda in 1994. The second workshop was in Addis Ababa, Ethiopia in 1995. The first preliminary probabilistic seismic hazard map for the region was prepared there. The third workshop was held in Bulawayo, Zimbabwe in 1996. At this workshop, significant improvements were made to the Addis Ababa hazard maps. Seismic source zone delineation was improved and different computational procedures tested. We present in this paper, results from the fourth workshop on hazard assessment in the Eastern and Southern Africa region. The work reported here is built upon the experiences gained from the previous three workshops and data compiled then.

2. Tectonics

Major tectonic features in the Eastern and Southern African region are mainly controlled by the well-known geological structure, the East African rift system. This feature extends as a continuous structure for approximately 4000 km from the triple junction in the Afar region joining the full spreading ridges in the Red-Sea and the Gulf of Aden in the north, to the less mature continental rifting that basically follows the mobile belts in the south (fig. 1). The age of the rifting varies from Tertiary to Recent; in some places rifting related to Karoo volcanic activity dates back to Permo-Triassic or Early Jurassic (King, 1970). In many places the structures within the rift have been influenced by the pre-existing Precambrian zones of weakness. Morphology of the rift resembles that of the mid-oceanic ridges with central rift valleys acting as depositional basins.

The rift basins are asymmetric and are bordered by curvilinear high angle border fault segments on one side and en echelon step faults with minor vertical offsets and flexural monoclines on the opposite side (Bosworth *et al.*, 1986; Rosendahl, 1987; Ebinger,1989; Dunkelman *et al.*, 1989; Chapola, 1997). Well developed grabens are only found in the Gregory and

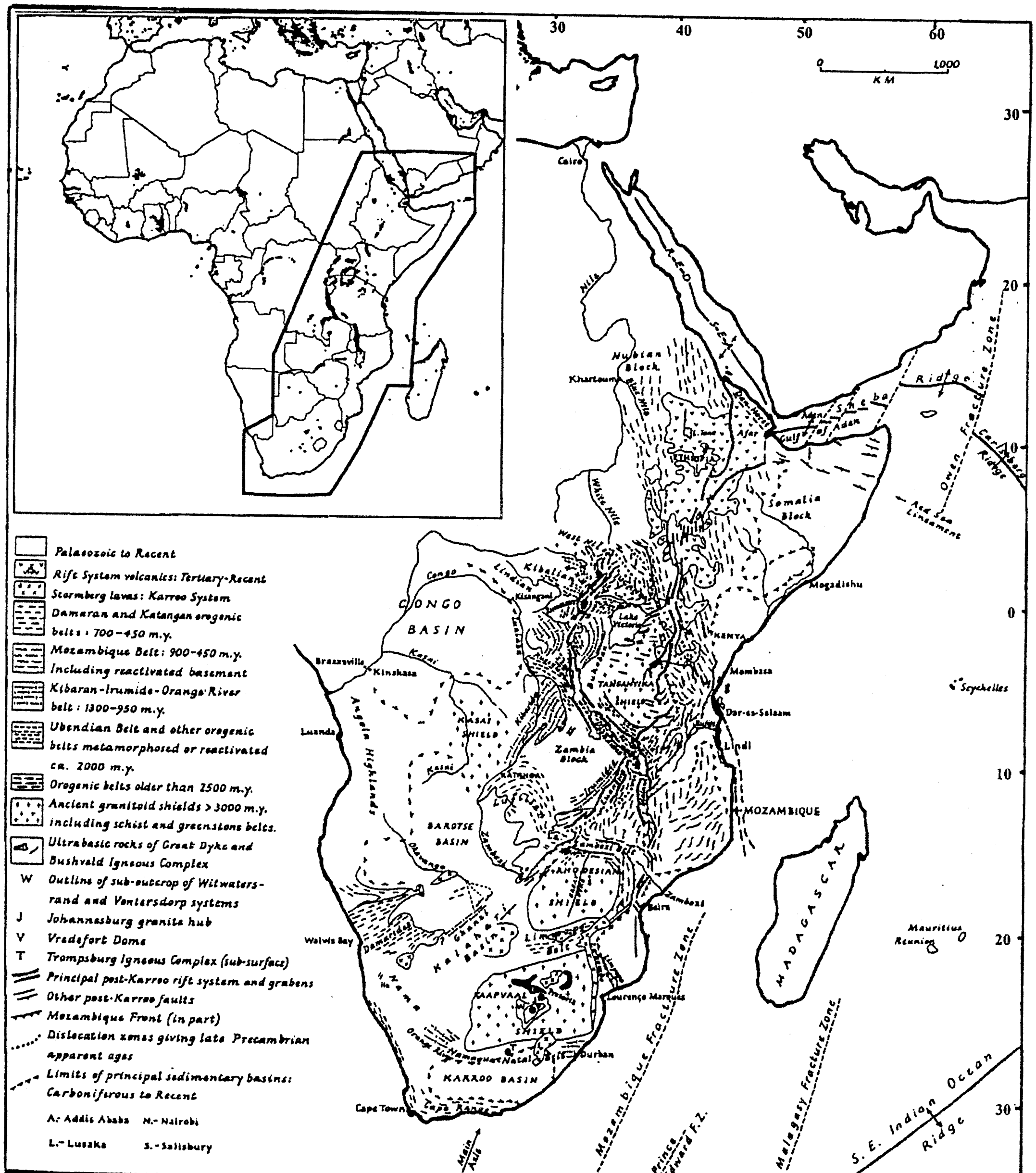

Fig. 1. The rift system of Eastern and Southern Africa in its geological setting. The inset shows the map of Africa with national boundaries. The bold outline of the inset marks the boundary of the area for which seismic hazard was computed. (Modified after McConnell, 1972).

Ethiopian rifts, while the rest of the rift is characterised by alternate half-grabens (Baker *et al.*, 1972). Individual half-grabens are separated from each other by accommodation zones which are complex structural highs made up of oblique-slip transfer faults, ramps and monoclines (Chapola, 1997). The accommodation zones act as transfer zones that allow switches in gross polarity of the border fault systems.

South of Ethiopia, the East Africa rift system breaks up into two branches, the western rift and the eastern rift. Continental rifting starts from the Afar triple junction and continues towards the south through the Ethiopian rift, joining into the Gregory rift in Kenya. This structure constitutes the eastern branch of the East Africa rift system. Further south, it branches into the Davie ridge (Mougenot *et al.*, 1986). The northern sector of this rift segment cuts across the abyssal plateau volcanics of Kenya. In Eastern Tanzania, the rift structures form a broad zone of faults defining a series of tilted blocks with varying orientations. Southeast of mount Kilimanjaro, the Pare-Usambara faults define a branch of the eastern rift which trends SE to join the fault systems of the Davie ridge in the Indian Ocean.

The western branch of the East Africa rift system extends from Northern Uganda to Southern Mozambique, encompassing the major lakes in the region such as the lakes Albert, Edward, Tanganyika and Malawi. Its northern boundary terminates abruptly in the Precambrian Aswa shear zone, a structure which stretches NW-SE from Southern Sudan through Uganda into Kenya. In the north, the rift is characterised by a N-S oriented zone that follows the earlier structural trends through the en echelon faults of the Albert Nile, lakes Albert, Edward, Kivu and Ruwenzori mountains. The E-W trending Katonga fault zone extends from north of lake Victoria towards the western rift. South of lake Kivu the fault orientations change from NNE-SSW to NNW-SSE. Major structures in this area are the border fault systems of lake Tanganyika and Rukwa that joins into the faults bordering lake Malawi.

In the south, the main features of the rift in the Malawi-Mozambique segment are border faults defining Lake Malawi. The southern extension of the lake Malawi rift is defined by faults bounding the Shire trough which extends to Urema trough and the Lebombo monoclinal structure in Southern Mozambique.

3. Seismicity

Earthquake activity in the Eastern and Southern Africa region is characterised by the occurrence of destructive earthquakes which are controlled by the well-known regional tectonic feature, the East Africa rift system. Figure 2 shows the distribution of earthquake epicentres in the region for the period 627-1994, for M_s magnitudes larger than 4.0. Activity is highest along the two spreading axes in the Red-Sea and the Gulf of Aden, which joins into the main Ethiopian Rift through the Afar triple-junction. Further to the south along the eastern branch, epicentre distribution is more diffuse than along the western branch where a concentration of epicentres follows the rift structures starting from Southern Sudan to Southern Malawi.

Activity continues to the south along the extension of the rift in Mozambique. Two branches from the western rift follow geological structures along belts in Southern Democratic Republic of the Congo into Western Zambia and along the Deka fault, mid-Zambezi valley and Luangwa rift. Activity in the eastern branch extends in to a broad zone in Tanzania and continues along the Davie ridge in the Indian Ocean. South of Zimbabwe, seismicity is generally sparse with epicentres concentrated along the eastern half and central northern Transvaal in South Africa. East-west oriented concentration of epicentres are observed in the southern tip of Africa around Cape Town while further to the south-east, the plate boundary-related seismicity appears as a NE-SW alignment of epicentres. On the other hand, the NE-SW oriented epicentre alignment around the co-ordinates 10°N and 20°E is probably due to mislocations (R. Adams, 1995, personal communication). The hypocentral depths are generally in the range 10-20 km. Recent results however, indicate that deep earthquakes (depths in excess of 30 km) have occurred in some segments of the rift (Jackson and Blenkinsop, 1993; Camelbeeck and Iran-

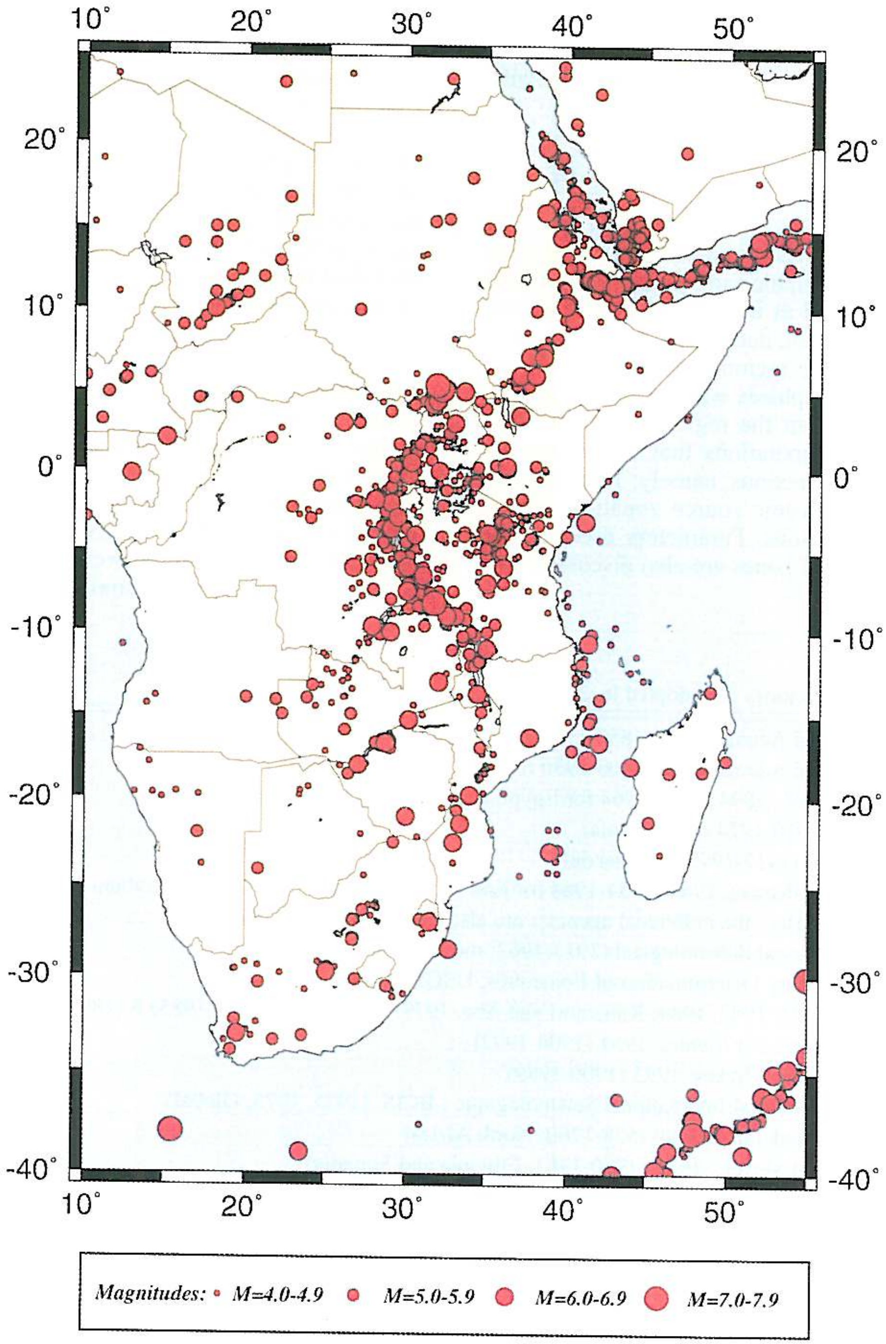

Fig. 2. Seismicity of Eastern and Southern Africa based on the catalogue compiled by Turyomurugyendo (1996). Earthquake epicentres are shown for $M_s \geq 4.0$.

ga, 1996; Nyblade *et al.*, 1996). These have confirmed earlier reports from micro-earthquake studies by Maasha (1975), Bungum and Nnko (1984).

4. Input data

Probabilistic seismic hazard analysis requires the use of all available earthquake data, *i.e.* both historical as well as instrumental, for a region. In this compilation, data prepared during previous studies in the region were used as primary data. Special emphasis was given to contributions to data from the region. The input data used in the computations that follow are described in three sections, namely: 1) earthquake catalogue; 2) seismic source zonation, and 3) attenuation relations. Parameters used for the individual source zones are also discussed separately.

4.1. *Earthquake catalogue*

The earthquake data used in this study is derived from the Earthquake Database for Eastern and Southern Africa (Turyomurugyendo, 1996). The data, compiled from a number of sources, cover the period 627-1994 and relate to an area bounded by latitudes, 40°S and 25°N and longitudes, 10°E-55°E. In his work, Turyomurgyendo found that for some events, different hypocentral and parametric solutions were given by different reporting agencies. In order to get the best solution, priority was given to the different agencies with emphasis on the individual specific studies from publications where the source parameters had been re-worked and improved upon. Table I shows the priority list of the different agencies adopted in preparing the catalogue for the period 627-1963. For the period 1964-1994, the priority solutions were kept as reported by the International Seismological Centre.

Table I. Source priority list adopted in data compilation.

1. Ambraseys and Adams, 1986 (1850-1981 for Sudan)
2. Ambraseys and Adams, 1992 (1900-1930 for Africa south of 20°N)
3. Ambraseys *et al.*, 1994 (1939-1964 for Egypt, Arabia, Red Sea)
4. Båth, 1975 (1910-1974 for Tanzania)
5. Maasha, 1975 (1912-1973 for Uganda)
6. Sykes and Landisman, 1964 (1954-1964 for East Africa, North Africa Red Sea, Arabian Sea)
7. USGS/NEIC. Here the individual agencies are also given priority as follows:
  7.1. International Seismological (1913-1963; the ISSN is included in ISS)
  7.2. Preliminary Determination of Epicentres, USGS (1868-1992)
  7.3. Abe, 1981, 1982, 1984; Kanamori and Abe, 1979; Abe and Noguchi, 1983a,b (1897-1980)
  7.4. Gutenberg and Richter, 1954 (1904-1992)
  7.5. Pacheco and Sykes, 1992 (1900-1989)
  7.6. Bureau Central International Seismologique , BCIS, (1935, 1975; Global)
  7.7. Poirier and Taher, 1980 (528-1760; North Africa)
  7.8. Riad and Meyers, 1985 (1900-1983; Ethiopia and Somalia)
  7.9. Catalogue of European earthquakes (2100 B.C.-1982; includes 7 sub-catalogues)
  7.10. Catalogue of earthquakes in Italy, ING, Rome (1450 B.C.-1984)
  7.11. Catalogue of earthquakes in the U.S.S.R. (150-1961)
  7.12. Constantinescu, 1980. Catalogue of earthquakes in Romania (984-1979)
8. Iranga, 1991 (1846-1988 for Tanzania)
9. Asfaw, 1992 (1904-1991 for Ethiopia)
10. Musson, 1994 (1071-1993 for sub-Sahara)
11. EAF/ESAF (for Ethiopia, *extension on NOAA catalogue*)

All magnitudes were homogenised to M_s and dependent events (foreshocks, aftershocks, induced events) were removed using the formulae suggested by Lazarov and Christoskov (1981). Catalogue completeness was carefully studied and the period 1900-1994 was found complete for magnitudes larger than 5.0.

4.2. *Seismic source zonation*

In seismic source zoning, a thorough analysis of the main tectonic structures and their correlation with present-day seismicity was the basis for the delineation of the source zones. The present study covers a large area of approximately 50° × 25°. At such a large scale, only regional structures could be accounted for in preparing the source zones. The detailed structures and individual faults were treated as broad fault zones that comprised area sources. Twenty-one area source zones were defined along the major rift segments (fig. 3). One possible way of improving the source zonation, especially for the site-specific studies, is the inclusion of fault sources to the area sources. This requires a detailed knowledge of the exact location and the extent of the individual faults or fault zones and the earthquake recurrence relations. Individual fault study and mapping was not carried out to enable this parameter to be input in the hazard computations in this study.

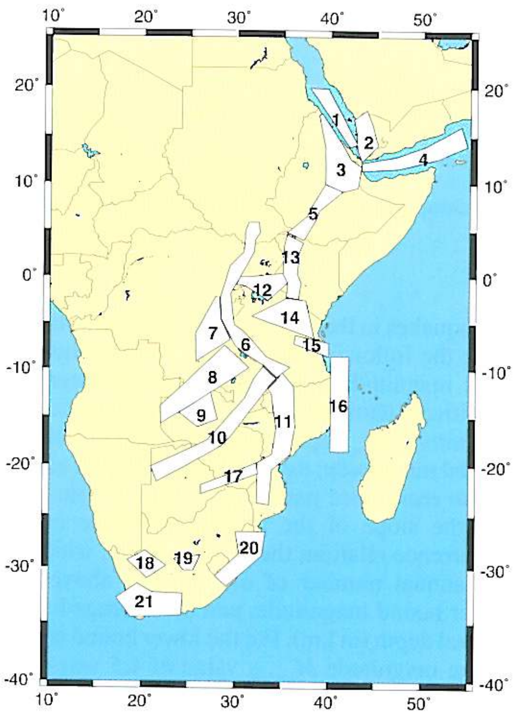

Fig. 3. The 21 seismic source zones used in the study. Note that zones cover basically the seismically active rift segments and areas where seismotectonic background knowledge is sufficient (see text for discussion).

4.3. *Attenuation*

Attenuation relations for the Eastern and Southern Africa region based on the strong motion data are virtually non-existent. However, attempts have been made recently by Jonathan (1996) and Twesigomwe (1997) to establish average attenuation relations for the region. Jonathan's relation is based on the random vibration theory using some recent earthquakes recorded by the digital stations in the region. Twesigomwe's relation, on the other hand, is a modification of the previously established relation by Krinitzky *et al.* (1988) using regional shear-wave velocity and Q values determined by other workers like Gumper and Pomeroy (1970).

These two relations are derived with data from the region under consideration in this study. The two relations are given here below

$$\ln a = 3.024 + 1.030 M_w - 1.351 \ln R - 0.0008 R \quad \text{(Jonathan, 1996)} \qquad (4.1)$$

$$\ln a = 2.832 + 0.866 M_s - \ln R - 0.0025 R + \varepsilon \quad \text{(Twesigomwe, 1997)} \qquad (4.2)$$

where, a is the ground acceleration (cm/s^2), R is the hypocentral distance (km) and ε is the error term.

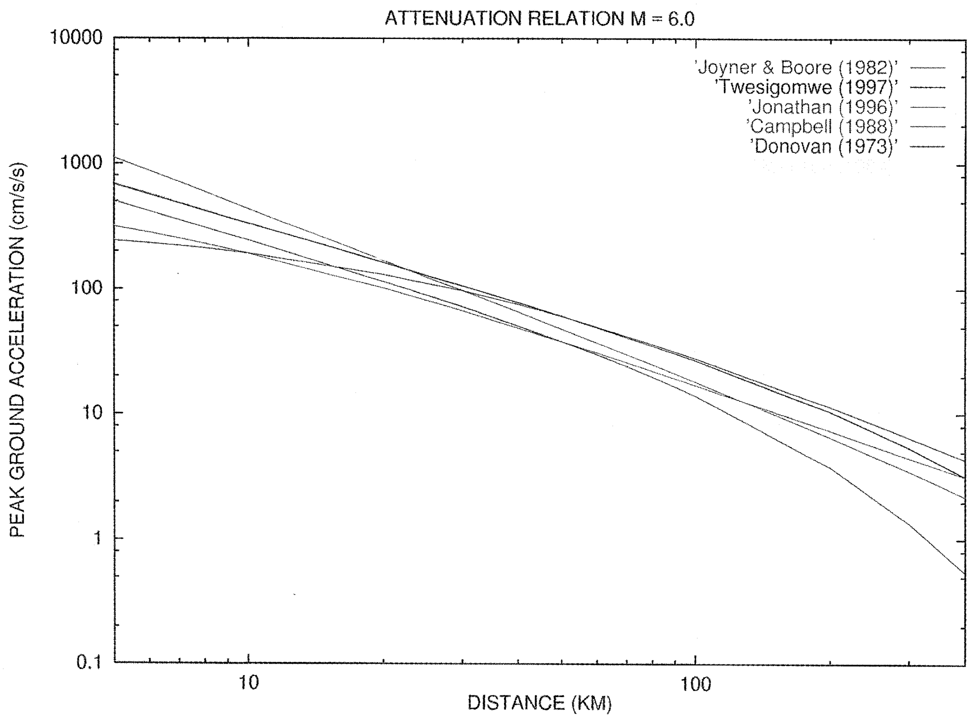

Fig. 4. The attenuation relations used in the seismic hazard computations shown together with some other known relations for comparison.

An attempt was made to compare the two attenuation curves given above with the Joyner and Boore (1982, 1988), Boore *et al.* (1993, 1994) relations. These relations are shown in fig. 4. The figure shows that there is close agreement between the regional attenuation relation curves and those widely used globally. For the hazard computations in this study, attenuation relations developed by Jonathan (1996) and Twesigomwe (1997) were adopted. A standard deviation of 0.6 for both relations was applied. Both relations were developed for hard rock conditions.

4.3.1. Input parameters for hazard computations

In addition to the attenuation relations, the major input for seismic hazard computations are the parameters used to define occurrence of earthquakes in the source zones. For each source zone the following parameters were evaluated: M_{low}, magnitude below which no engineering-significant damage is expected; the upper bound magnitude M_{upp} representing the maximum expected magnitude; the Gutenberg-Richter earthquake recurrence parameter b-value, representing the slope of the magnitude-frequency of occurrence relation; the activity rate λ, which is the annual number of earthquakes above the lower bound magnitude; and the average hypocentral depth (in km). For the lower bound earthquake magnitude M_{low}, a value of 4.5 was chosen. This magnitude was considered to be of significance to engineering applications in the region. These parameters were obtained using the SEISAN software (Havskov, 1997), on the selected data from the earthquake catalogue corresponding to each source zone. Since the data used is complete for magnitude $M_s \geq 5.0$ it was necessary to consider the incomplete portions of the data in the calculations of the b-value for the determination of β value. For this, an estimation method for calculating the b-value (Weichert, 1980) that takes into account incompleteness was used. The calculated parameters are given in table II.

Table II. Input parameters for the area source zones.

Source zones	M_{low}	M_{upp}	β	λ
Source zone 1	4.5	6.7	2.08	0.64
Source zone 2	4.5	7.1	2.28	0.16
Source zone 3	4.5	6.8	1.57	1.24
Source zone 4	4.5	6.5	2.44	2.54
Source zone 5	4.5	6.8	1.33	0.39
Source zone 6	4.5	7.8	2.08	3.17
Source zone 7	4.5	7.8	2.79	0.43
Source zone 8	4.5	7.1	2.24	0.46
Source zone 9	4.5	7.1	2.37	0.07
Source zone 10	4.5	7.1	1.64	0.42
Source zone 11	4.5	7.3	2.14	0.70
Source zone 12	4.5	6.7	2.90	0.55
Source zone 13	4.5	7.4	1.37	0.14
Source zone 14	4.5	7.4	2.41	1.20
Source zone 15	4.5	7.4	2.94	0.06
Source zone 16	4.5	7.0	2.10	0.54
Source zone 17	4.5	7.2	1.58	0.05
Source zone 18	4.5	7.2	2.94	0.09
Source zone 19	4.5	7.2	2.37	0.13
Source zone 20	4.5	7.2	1.97	0.16
Source zone 21	4.5	7.2	1.58	0.15

Abbreviations: M_{low} = lower bound magnitude; M_{upp} = maximum expected upper bound magnitude; b-value = slope of magnitude-frequency relation; β = ln (10) × b-value; λ = activity rate.

5. Seismic hazard analysis

5.1. *A brief review of the theory*

Probabilistic seismic hazard analysis applied in this study is based on the widely used standard methodology developed by Cornell (1968), McGuire (1974; 1976) and Der Kiureghian and Ang (1975, 1977). The computer program used in the analysis, FRISK88M (Risk Engineering Inc., 1996), uses the total probability theorem in calculating the probability of a given ground motion a (*e.g.*, peak ground acceleration, velocity or displacement) being exceeded at a given site, which can be represented by the following equation:

$$H(a) = \sum_i \nu_i \int\int P[A > a \mid m, r] f_{R_i}(r \mid m) f_{M_i}(m) dr dm \tag{5.1}$$

where the hazard $H(a)$ is the annual rate of earthquakes that produce a ground-motion amplitude A higher than a. $P[A > a|m, r]$ is the probability that the ground motion at the site due to a given earthquake of magnitude m and the hypocentral distance r will exceed ground motion level a. Parameter $f_{Mi}(m)$ is the independent probability density function of m, while $f_{Ri}(r)$ is the probability density function of r given m. The summation in eq. (5.1) extends over all source sets, where ν_i is the annual rate of earthquakes in source set i, with magnitude higher than the chosen threshold.

For area sources, $P[A > a|m, r]$ is obtained from the attenuation function of the form

$$\ln A = C_1 + C_2 M + C_3 \ln(R + R_0 A) + C_4 R + \varepsilon; \quad \varepsilon \sim N(0, \sigma_\varepsilon^2) \tag{5.2}$$

where R is focal distance (assuming a point source), C_1, C_2, C_3 and C_4, R_0A, and σ_ε are constants independent of M and R.

The distribution of magnitude is assumed to be a doubly truncated exponential of the form

$$f_{M_i}(m) = k_i \beta_{\varepsilon i} \exp(-\beta_i(m - M_{0i})), \quad M_{(0i)} \le m \le M_{maxi} \tag{5.3}$$

in which $k_i = (1 - \exp(-\beta_i(M_{maxi} - M_{0i})))^{-1}$ is a normalising constant, $M_{(0i)}$ is the chosen threshold magnitude and M_{maxi} is the largest magnitude that may occur in the source; M_{0i} and M_{maxi} are respectively equal to M_{low} and M_{upp} as given in table II.

5.2. *Seismic hazard results*

The probabilistic seismic hazard for Eastern and Southern Africa is computed using the software FRISK88M (Ver. 1.70), provided by the Risk Engineering Inc. (1996) of Boulder, Colorado, U.S.A. Uncertainty in the inputs to the analysis was treated using a logic-tree approach (Kulkarni *et al.*, 1986; EPRI, 1986; McGuire *et al.*, 1986; Toro and McGuire, 1987). Two alternatives were used for the attenuation relation (with equal weight of 0.5 each), two different depth estimates (10 and 30 km, with 0.4 and 0.6 weights respectively) were also incorporated in the logic-tree as two alternatives. The logic-tree examples for the computations are shown in fig 5.

The results obtained from the hazard computations are shown graphically in figs. 6 to 9. Figures 6 and 7 show the mean PGA values (in gals) for a 10% probability of exceedance in 50 and 100 years; figs. 8 and 9 are for 50 and 100 years return periods. These figures show that high PGA values were obtained for all cases for the western Gulf of Aden, Afar depression, Southern Sudan, western rift and Northern Tanzania. For example, high mean PGA values in excess of 240 gals for 10% exceedance in 100 years and 100 gals for a 100 years return period are obtained for the regions mentioned above.

6. Discussion and conclusions

The high PGA values obtained for the western rift and the Afar regions may be attributed to the high seismic activity in the regions. On the other hand, the high PGA values obtained for Southern Sudan and Northern Tanzania could be due to the occurrence of large magnitude earthquakes, in Southern Sudan in 1990 ($M_S = 7.1$), and in Tanzania in 1910 ($M_S = 7.4$) (Ambraseys and Adams, 1992). The two attenuation relations used in this study gave slightly lower PGA values compared to previous studies. This is so especially for those areas in the southern part of the region. This difference may be attributed to the different input parameters, different source zones and computational software used. Considering the fact that most developments within the region are concentrated along the areas of rifting and that the southern part of the region,

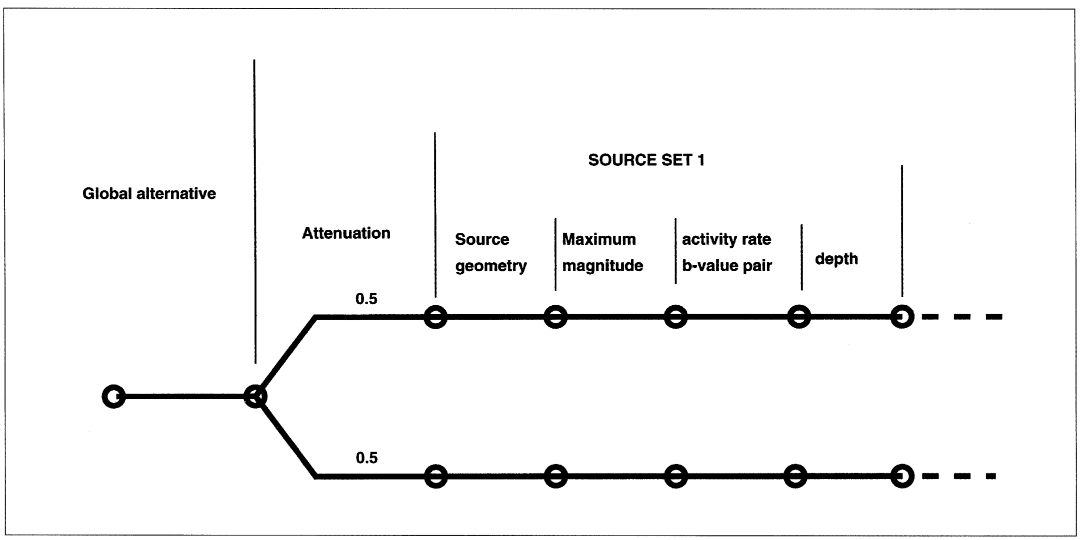

Fig. 5. Logic-tree examples shown for the regional computations.

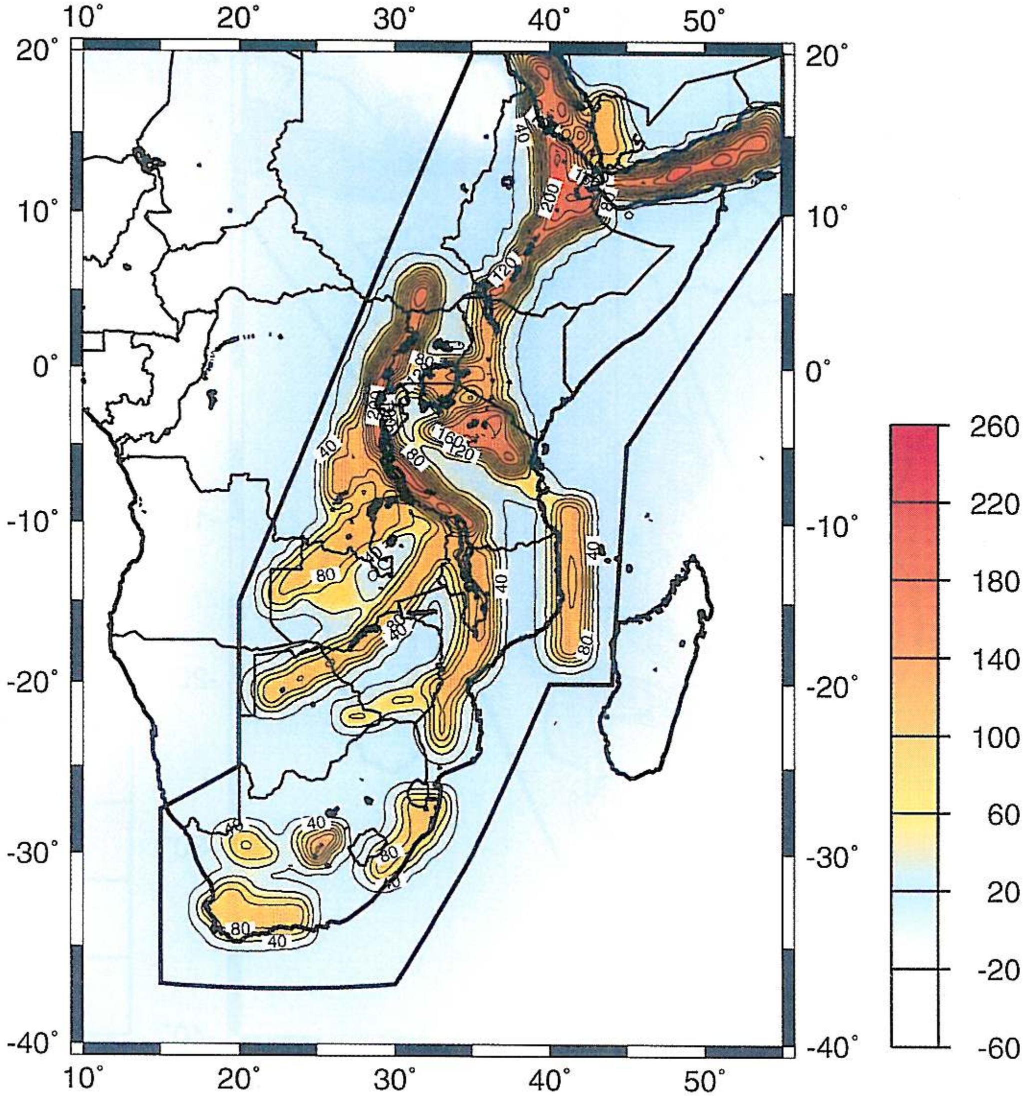

Fig. 6. Distribution of mean PGA (in gals) values in Eastern and Southern Africa computed for 10% probability of exceedance in 50 years (contour interval is 40 gals).

though characterised by relatively lower hazard, is an area of incipient rifting, there is a need to assess the earthquake hazard, particularly in city and town planning and in the construction of high-rise buildings and water reservoirs. For the nine cities selected as special sites in this study, PGA values vary depending on the return period of interest and the degree of conservatism (*i.e.* the different percentiles). In this report several different sets of seismic hazard results were produced and presented. However, proper choice of the return period with the desired level of

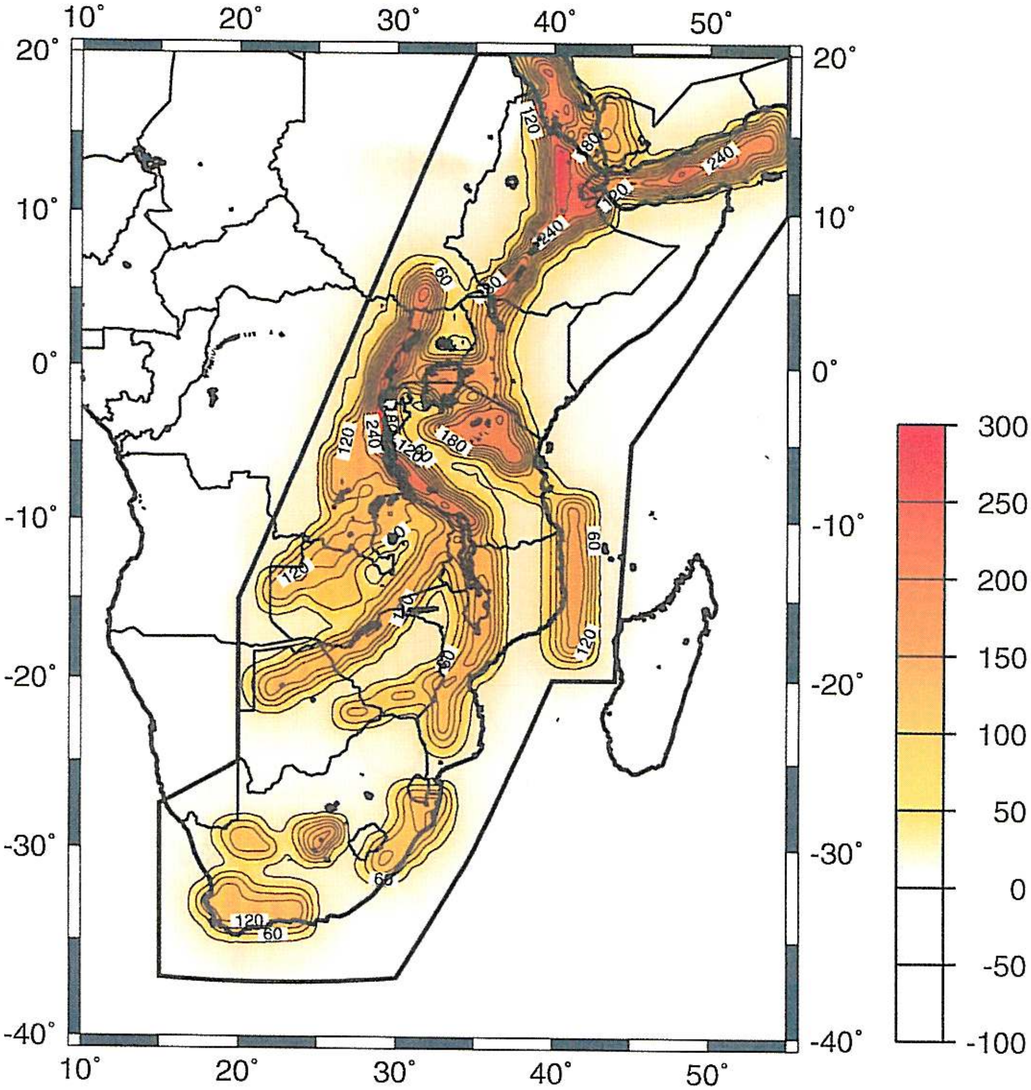

Fig. 7. Distribution of mean PGA (in gals) values in Eastern and Southern Africa computed for 10% probability of exceedance in 100 years (contour interval is 40 gals)

conservatism, is the end-user's (*i.e.* the structural design engineer, the city planner or the decision maker) responsibility. Furthermore, site specific studies presented here are only for hard rock conditions, and hence future studies that take into account soil type and local geology are necessary before a realistic assessment of the earthquake hazard can be made. Efforts should be directed towards investigating the attenuation relations for average soil types in the region. This, as well as the recently available spectral attenuation relations (Spudich *et al.*,

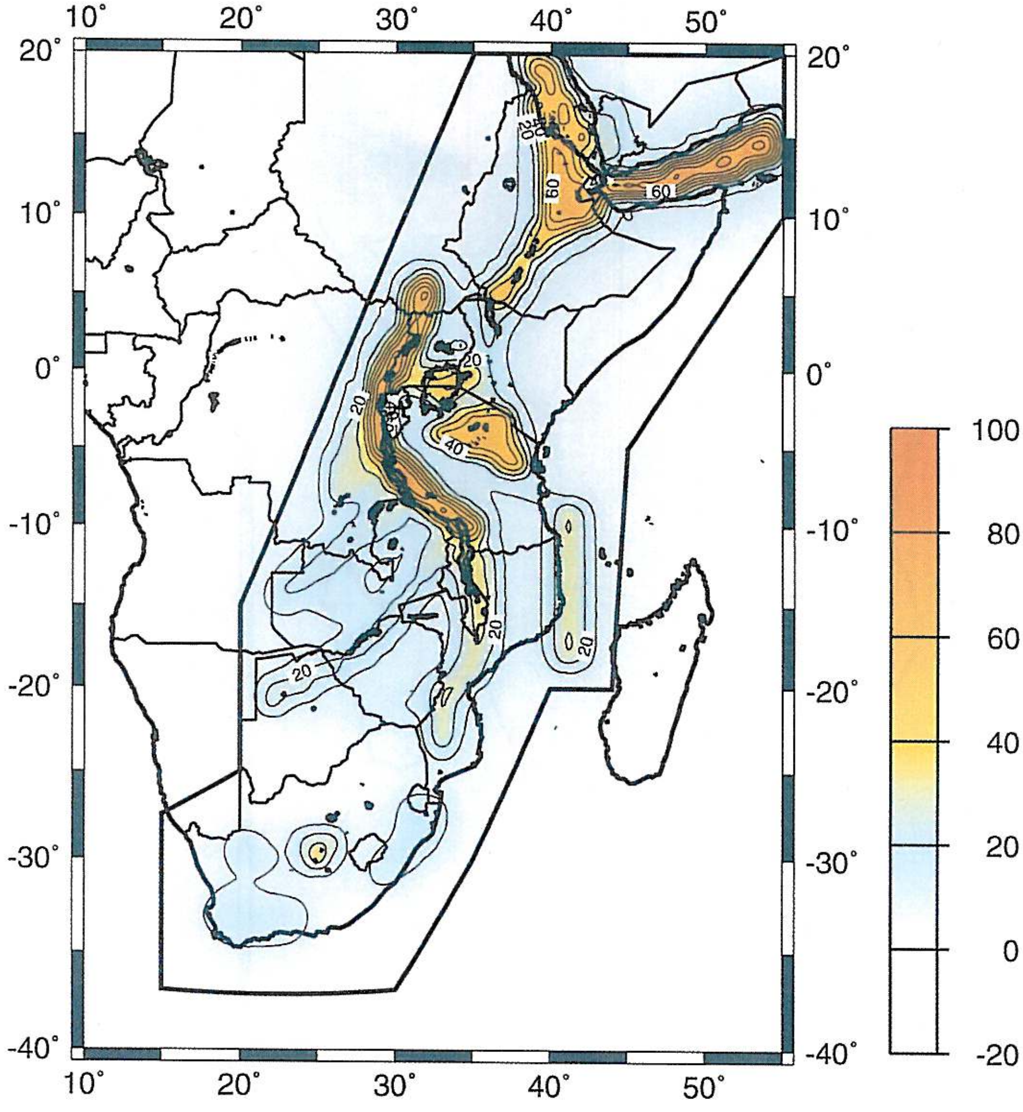

Fig. 8. Distribution of mean PGA (in gals) values in Eastern and Southern Africa computed for a return period of 50 years (contour intervals is 10 gals).

1997), may be used in the future for improving the results.

Seismic hazard assessment for the Eastern and Southern Africa region is an ongoing process which will also continue in the future. In this respect, the regional probabilistic hazard estimates obtained during this workshop represent the state-of-the-art results and should be regarded as guidelines on a regional scale. On local scales however, specific studies are needed. Detailed seismic hazard analyses which already exist for some of the countries, will provide

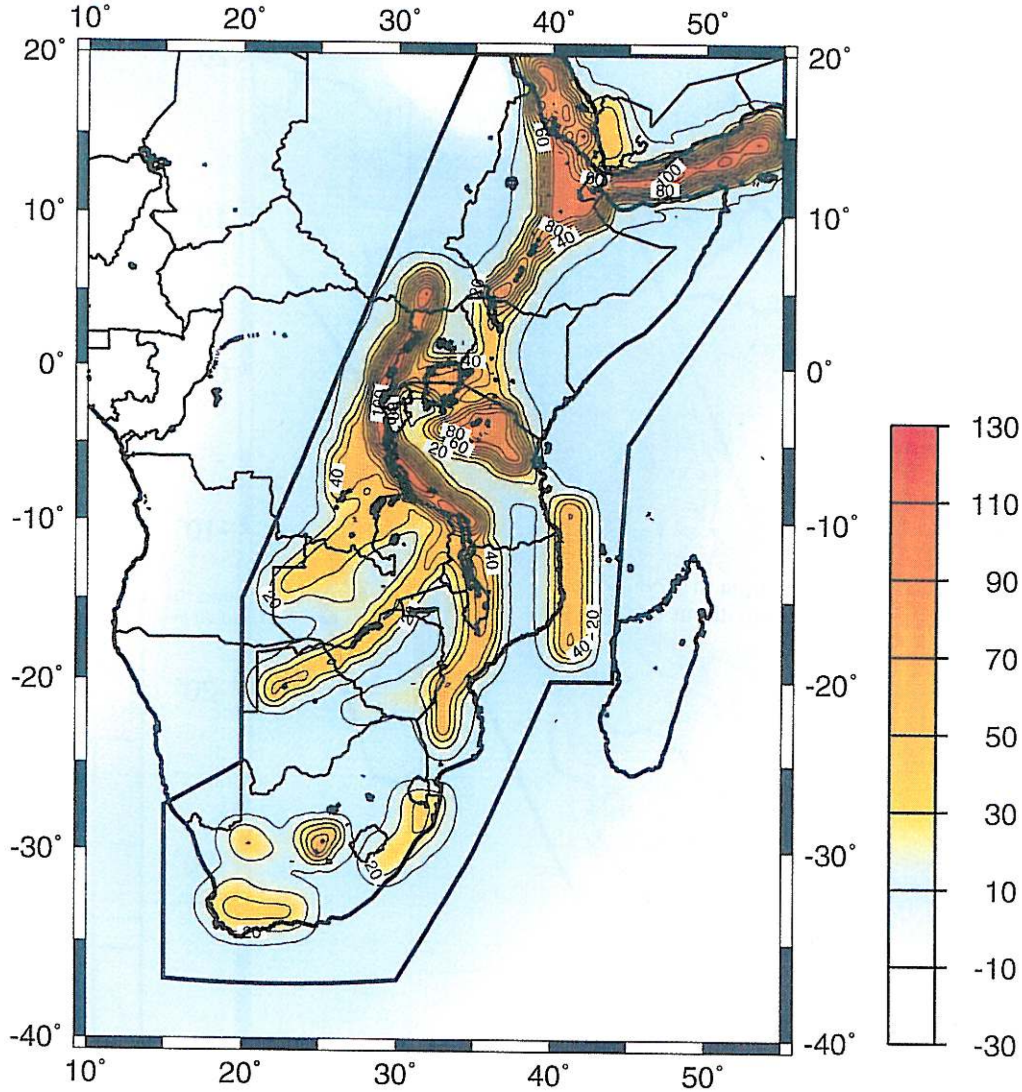

Fig. 9. Distribution of mean PGA (in gals) values in Eastern and Southern Africa computed for a return period of 100 years (contour interval is 10 gals).

major contributions to this end. Obviously, significant improvements may be achieved both in local and regional scales, once the seismotectonic knowledge of the area as well as the attenuation relations, are better understood. During this study, some of the attention was also drawn into the seismic hazard related to the major population centres in the region, where individual results were produced. Earthquake hazard and risk for megacities in the region as well as all around the world remain be a major challenge for future work.

Acknowledgements

Financial support for some of the participants was provided by the International Lithosphere Program (ILP) through the Global Seismic Hazard Assessment Program (GSHAP). We thank GSHAP co-ordinator, Prof. Domenico Giardini, for this continued support. The software used in computing the probabilistic seismic hazard (FRISK88M, Ver.1.70), was kindly provided by Risk Engineering Inc., of Boulder, Colorado, U.S.A. under the GSHAP. We thank Dr. Robin McGuire for his support on this. This work would certainly not have materialised without the financial support of the International Programme in Physical Sciences (IPPS), Uppsala Sweden and the untiring support rendered to the Group by the IPPS Director, Prof. Lennart Hasselgren in hosting earlier workshops in the region where the preliminary work was done, first, in Addis Ababa, Ethiopia in 1995, secondly, in Zimbabwe in 1996. Without this support and ground work, it would have been virtually impossible to carry out the hazard assessment reported here. We are also thankful to UNESCO and IASPEI for contributing some funding at various workshops related to the preliminary work on seismic hazard in this region.

Data processing for the input parameters were done using the software SEISAN. We are grateful to Jens Havskov for making his software available to us. The director of the Institute of Solid Earth Physics, Jens Havskov, is also thanked for providing the facilities for the workshop and for his help in some of the computational problems and to Bodil Helsengreen and Norbjørg Kaland, we are truly grateful for their help in many practical aspects. Lastly, we sincerely thank the participants of the Addis Ababa and Bulawayo ESARSWG workshops who could not participate in the work at Bergen Norway (these are: Jamal A. Abdulla, Robin Adams, Laike M. Asfaw, Daniel Ghebretatios, Isaac Marobhe, Lovemore Masawi, Samuel Muchuku, Ian Saunders, Alice Walker, Harris Nyali, Mubu S. Mubu, Ezra Twesigomwe, Ghebrebrham Ogubazghi, Andre Kijko, Thomani Shumba, Patrick Ngulube, Ted Gumbi) for the preliminary work done upon which we were able to build our study in Bergen, Norway.

REFERENCES

ABE, K. (1981): Magnitudes of large shallow earthquakes from 1902 to 1980, *Phys. Earth Planet. Inter.*, **27** (1), 72-92.

ABE, K. (1982): Magnitude, seismic moment and apparent stress for major deep earthquakes, *J. Phys. Earth*, **30** (4), 321-330

ABE, K. (1984): Complements to «Magnitude of large shallow earthquakes from 1904 to 1980», *Phys. Earth Planet. Inter.*, **34** (1-2), 17-23.

ABE, K. and S. NOGUCHI (1983a): Determination of magnitude for large shallow earthquakes 1898-1917, *Phys. Earth Planet. Inter.*, **32** (1), 45-59.

ABE, K. and S. NOGUCHI (1983b): Revision of magnitudes of large shallow earthquakes 1897-1912, *Phys. Earth Planet. Inter.*, **33** (1), 1-11.

AMBRASEYS, N.N. and R.D. ADAMS (1986): Seismicity of the Sudan, *Bull. Seismol. Soc. Am.*, **76**, 483-493.

AMBRASEYS, N.N. and R.D. ADAMS (1992): Reappraisal of major African earthquakes, *Natural Hazards*, **4**, 389-419.

AMBRASEYS, N.N., C.P. MELVILLE and R.D. ADAMS (1994): *The Seismicity of Egypt, Arabia and the Red Sea, a Historical Review* (Cambridge Press), p. 181.

ASFAW, L.M. (1992): Seismic risk at a site in the East African rift system, *Tectonophysics*, **209**, 301-309.

ATKINSON, G.A. (1984): Attenuation of strong ground motion in Canada from random vibration approach, *Bull. Seismol. Soc. Am.*, **74**, 2629-2653.

BAKER, B.H., P.A. MOHR and L.A. WILLIAMS (1972): Geology of eastern rift system of Africa, *Geol. Soc. Am.* (special paper), **136**.

BÅTH, M. (1975): Seismicity of the Tanzania region, *Tectonophysics*, **27**, 353-379.

BÅTH, M. (1979): *Introduction to Seismology* (Birkhauser), 2nd edition, 137-167.

BOORE, D.M, W.B JOYNER and T.E. FUMAL (1993): Estimation of response spectra and peak accelerations from Western North American earthquakes: an interim report, *U.S. Geol. Surv. Open-File Rep. 93-509*, p. 72.

BOORE, D.M, W.B. JOYNER and T.E. FUMAL (1994): Estimation of response spectra and peak accelerations from Western North American earthquakes: an interim report, Part 2, *U.S. Geol., Surv. Open-File Rep. 94-127*, p. 40.

BOSWORTH, W., J. LAMBIASE and R. KIESLER (1986): A new look at Gregory's rift: the structural style of continental rifting, *Eos, Trans. Am. Geophys. Un.*, 577-582.

BUNGUM, H. and A.A. NNKO (1984): Seismicity and tectonics of the Stiegler's Gorge area, Tanzania. *J. Geophys. Res.*, **89**, 1874-1888.

CAMASSI, R., S. MIRENNA, A. REBEZ, M. STICCHI and A. ZERGA (1995): Problems and pitfalls in the compilation of comprehensive, parametric earthquake catalogues, Materials of the CEC Project *«Review of Historical Seismicity in Europe»*, vol. 2.

CAMELBEECK, T. and M.D. IRANGA (1996): Deep crustal earthquakes and active faults along Rukwa trough, Eastern Africa, *Geophys. J. Int.*, **124**, 612-630.

CAMPBELL, K.W. (1985): Strong motion attenuation relations: a ten-years perspective, *Earthquake Spectra*, **1** (4), 759-804.

CHAPOLA, L.S. (1997): State of stress in east and Southern Africa and seismic hazard analysis of Malawi, *Unpubl. M.Sc. Thesis*, Institute of Solid Earth Physics, University of Bergen, Bergen, Norway, p. 143.

CONSTANTINESCU, L. (1980): Review of «Seismological study of the earthquake of 4th March 1977» edited by I. COTRNEA and C. RADU, in Romanian, *Studii Cerc. Geol. Geofiz. Geogr., Ser. Geofiz.*, **18**, 195-198.

CORNELL, C.A. (1968): Engineering seismic risk analysis, *Bull. Seismol. Soc. Am.*, **18**, 1583-1606.

DER KIUREGHIAN, A. and A. H.-S. ANG (1975): A line source model for seismic risk analysis, *University Illinois Technological Report*, UILU-ENG-75-2023, Ureana, p. 134.

DER KIUREGHIAN, A. and A. H.-S. ANG (1977): A fault-rupture model for seismic risk analysis, *Bull. Seismol. Soc. Am.*, **67**, 1173-1194.

DONOVAN, N.C. (1973): Earthquake hazards for buildings, in building practices for disaster mitigation, *Nat. Bur. Stand. Build. Sci. Ser.*, **46**, 82-111.

DUNKELMAN, T.J., B.R. ROSENDAHL and J.A. KARSON (1989): Structure and stratigraphy of Turkana rift from seismic reflection data, *J. African Earth Sci.*, **8**, 489-510.

EBINGER, C.J. (1989): Tectonic development of western branch of the East African rift system, *Geol. Soc. Am. Bull.*, **101**, 885-903.

EPRI (1986): Seismic hazard methodology for the Central and Eastern United States, Electric Power Research Institute, *Report NP-4726*, vol. 1, July.

GUMPER, F. and P.W. POMEROY (1970): Seismic wave velocities and earth structure on the African continent, *Bull. Seismol. Soc. Am.*, **60**, 651-668.

GUTENBERG, B. and C. RICHTER (1954): Seismicity of the Earth and associated phenomena (Princeton Univ. Press), pp. 310.

HAVSKOV, J. (1997): SEISAN (Version 6.0). *Earthquake Analysis Software for the IBM-PC and SUN*, Institute of Solid Earth Physics, University of Bergen, Norway, p. 236.

IRANGA, D.M. (1991): An earthquake catalogue for Tanzania 1846-1988, Uppsala University *Report No. 1-91*.

JACKSON, J. and T. BLENKINSOP (1993): The Malawi earthquake of March 10, 1989: deep faulting within East African rift system, *Tectonics*, **12**, 1131-1139.

JONATHAN, E. (1996): Some aspects of seismicity in Zimbabwe and Eastern and Southern Africa, *M. Sc. Thesis*, Institute of Solid Earth Physics, University Bergen, Bergen, Norway, p. 100.

JOYNER, W.B. and D.M. BOORE (1982): Prediction of earthquake response spectra, *U.S. Geol. Surv. Open-File Rep. 82-977*, p. 16.

JOYNER, W.B. and D.M. BOORE (1988): measurement, characterisation and prediction of strong ground motion, in *Proceedings Earthquake Engineering Soil Dynamics II, GT Div/ASCE, Park City, UT, June 27-30, 1988*.

KANAMORI, H. and K. ABE (1979): Reevaluation of the turn of the century seismicity peak, *J. Geophys. Res.*, **84** (11), 6131-6139.

KING, B.C. (1970): Vulcanicity and rift tectonics in East Africa, in *African Magmatism and Tectonics*, edited by T.N. CLIFFORD and I.G. GASS (Oliver and Boyd Publ.).

KRINITZKY, E.L, F.K. CHANG and O.W. NUTTLI (1988): Magnitude related earthquake ground motion, *Bull. Ass. Eng. Geol.*, **25**, 399-423.

KULKARNI, R.B., R.R. YOUNGS and K.J. COPPERSMITH (1986): Assessment of confidence intervals for results of seismic hazard analysis, in *Proceedings, Eight World Conference on Earthquake Engineering, San Francisco, July 1984*, pp. 263.

LAZAROV, R. and L. CHRISTOSKOV (1981): Statistical aspects of the magnitude-frequency relation for Bulgaria, in *Proceedings of the 2nd International Symposium on the «Analysis of Seismicity and on Seismic Hazard», Liblice, Czechoslovakia, May 18-23, 1981*, 56-66.

MAASHA, N. (1975): The seismicity and tectonics of Uganda, *Tectonophysics*, **27**, 381-393.

MCCONNELL, R.B. (1972): Geological development of the rift system of East Africa, *Bull. Geol. Soc. Am.*, **83**, 2549-2572.

MCGUIRE, R.K. (1974): Seismic structural response risk analysis, incorporating peak response regressions on earthquake magnitude and distance, Mass. Tech., Dept. of Civil Eng., *Publication No. 399*, p. 371.

MCGUIRE, R.K. (1976): FORTRAN computer program for seismic risk analysis, *U.S. Geol. Survey Open-File Rep. 76-67*, p. 90.

MCGUIRE, R.K., J.C. STEPP and G.R. TORO (1986): Seismic hazard and its uncertainty in the Eastern U.S. Proceedings, *Annual Meeting of the Society of Risk Analysis, Boston*.

MOUGENOT, D., M. RECQ, P. VIRLOGEUX and C. LEPVRIER (1986): Seaward extension of the East African rift. *Nature*, **321**, 599-603.

MUSSON, R.M.W. (1994): The BGS Sub-Saharan African earthquake catalogue, *Br. Geol. Sur. Tech. Rep., WL/94/28*.

NYBLADE, A.A., C. BIRT, C.A. LANGSTON, T.J. OWENS and R.J. LAST (1996): Seismic experiment reveals rifting in craton of Tanzania. *Eos, Trans. Am. Geophys. Un.*, **77**, 517-521.

PACHECO, J.F. and L.R. SYKES (1992): Seismic moment catalogue of large shallow earthquakes, 1900 to 1989, *Bull. Seismol. Soc. Am.*, **82**, 1306-1349.

POIRIER, J.D. and M.A. TAHER (1980): Historical seismicity in the Near and Middle East, North Africa, and Spain from Arabic documents (VIIth-XVIIIth century), *Bull. Seismol. Soc. Am.*, **70** (6), 2185-2201.

REITER, L. (1990): *Earthquake Hazard Analysis, Issues and Insights* (Columbia University Press.), 9-29.

RISK ENGINEERING INC. (1996): FRISK88M (Version 1.70). User's Manual. 4155 Darley Av., Suite A, Boulder, Colorado 80303 U.S.A.

ROSENDAHL, B.R. (1987): The architecture of continental rifts with special reference to the East Africa, *Ann. Rev. Earth Planet. Sci.*, **15**, 445-503.

SPUDICH, P., J.B. FLETCHER, M. HELLWEG, J. BOATWRIGHT, C. SULLIVAN, W.B. JOYNER, T.C. HANKS, D.M. BOORE, A. MCGARR, L.M. BAKER and A.G. LINDH (1997): SEA96 - A new predictive relation for earthquake ground motions in extensional tectonic regimes, *Seismol. Res. Let.*, **68**, 190-198.

SYKES, L.R. and M. LANDISMAN (1964): The seismicity of East Africa, the Gulf of Aden and the Arabian and Red Seas, *Bull. Seismol. Soc. Am.*, **54**, 1927-1940.

TORO, G.R. and R.K. MCGUIRE (1987): Calculational procedures for seismic hazard analysis and its uncertainty in Eastern U.S., in *Proceedings, Third International Conference on Soil Dynamics and Earthquake Engineering, Princeton.*

TURYOMURUGYENDO, G. (1996): Some aspects of seismic hazard in the East and South African region, *M.Sc. Thesis*, Institute of Solid Earth Physics, University of Bergen, Bergen, Norway, p. 80 (unpublished).

TWESIGOMWE, E. (1997): Probabilistic seismic hazard assessment of Uganda, *Ph.D. Thesis*, Dept. of Physics, Makarere University, Uganda.

USGS/NEIC (1994): United States Geological Survey, National Earthquake Information Center. Global Hypocenter Database (CD-ROM), *EPIC User's Guide* (Version 3.0), Appendix B, September.

VANEK, J., A. ZATOPEK, V. KARNEIK, N. KONDORSKAYA, Y. RIZNICHENKO, E. SOVAOENSKI, S. SOLOV'EV and N. SHEBALIN (1962): Standardisation of magnitude scales, *Izv. Acad. Sci. USSR, Geophys. Service*, **2**, 153-158.

WEICHERT, H.D. (1980): Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes, *Bull. Seismol. Soc. Am.*, **70**, 1337-1346.