A SEISMIC SOURCE MODEL FOR WEST AFRICA

Grace CAMPBELL¹, Zygmunt LUBKOWSKI², Manuela VILANI³, Barbara POLIDORO⁴,

ABSTRACT

West Africa is considered to be a region of low seismicity, yet in spite of this, the region has experienced destructive historical earthquakes such as the 1939 Accra, Ghana earthquake which killed 22 people and left about 130 injured. Today, parts of Ghana, Nigeria and Cameroon continue to experience moderate and smaller magnitude earthquakes, highlighting that the seismic hazard in these regions cannot be ignored. In combination with rapid population growth and rapid urbanisation, cities in these regions need to consider earthquake hazard in their design to ensure greater resilience to earthquake hazards. This paper presents a new synthesis of the seismotectonics of West Africa, including a discussion of the potential active faults and an updated earthquake catalogue, with a view to informing future seismic hazard studies. Using the inputs described above we present preliminary estimates of the peak ground acceleration (PGA) mean seismic hazard curves for six of the most populated cities in West Africa.

Keywords: Earthquake hazard; West Africa; Seismotectonics; Seismic design; Stable Continental Region

1. INTRODUCTION

West Africa is remote from any major active plate boundary and deforms very slowly (<2mm/year; Deprez et al. 2013), yet in spite of this, moderate yet destructive earthquakes have occurred in the recent historical past (e.g. Adam and Ambraseys, 1986), as shown in Figure 1. Some of this seismicity is associated with known active faulting, for example along the Atlantic margin, and with the ongoing volcanic activity of the Cameroon Volcanic Line (CVL). Other moderate earthquakes have occurred within the continent on faults that are less well known (Figure 1). From a seismicity perspective the region is considered a stable continental region (SCR) as described by Johnston et al, (1994). However, a number of authors have discussed active faulting and seismicity in West Africa (e.g. Junner, 1914; Burke, 1969; etc.) highlighting the significance of earthquake hazards in the region.

It is well known that major earthquakes have occurred in similar SCRs in other parts of the world resulting in high social and economic impacts. Three unrelated examples are the Mw 6.2 1993 Latur India earthquake that caused over 8,000 fatalities and $300 million in damage (Greene et al. 2000), the 1811-1812 M7.5 New Madrid earthquake sequence in the central US were felt strongly over roughly 130,000km² and the 1356 M6.7 Basel, Switzerland, which devastated the city with more than 300 fatalities (Fäh et al. 2011). In southern Ghana, destructive earthquakes with magnitude 5.5 and 6.5 have occurred in the recent historical past and there is enough historical evidence to indicate that a repeat event of similar magnitude today would result in much more widespread destruction and many more fatalities than historically possible. Over the recent historical past, death rates in earthquakes within continental interiors, similar to regions such as West Africa, have often exceeded 5%, and can be as high as 30% of the exposed population (England and Jackson, 2011); and, as highlighted by England and Jackson (2011), knowledge of the earthquake hazard in these regions is a key tool in developing resilience to future potentially devastating events.

¹Earthquake Geologist, Ph.D. Ove Arup & Partners, London, UK, grace.campbell@arup.com
²Associate Director, Ove Arup & Partners, London, ziggy.lubkowski@arup.com
³Senior Engineer, Ph.D. Ove Arup & Partners, London, manuela.villani@arup.com
⁴Engineer, Ph.D. Ove Arup & Partners, London, barbara.polidoro@arup.com
Review of previous seismic hazard studies and codes for West Africa indicate appropriate information is limited. The GSHAP global seismic hazard map (Giardini et al. 1999) suggests the hazard in the region is very low. In contrast Worku (2014) reviewed several seismic codes in sub-Saharan countries and concluded the Ghanaian code suffers from flaws in the background seismic hazard assessment study that led to the unrealistic high seismic zone factors. A better understanding of the seismic hazard for the region is therefore critical, particularly since rapid urbanisation and population growth within many of coastal cities means that there is a large vulnerable population.

Figure 1. Study area in West Africa. Cities for which preliminary seismic hazard estimates have been calculated are shown along with the entire earthquake catalogue compiled for this study. Earthquakes with dates and yellow centres have magnitudes greater than 5.5.

2. GEOLOGY AND SEISMOTECTONICS OF WEST AFRICA

The geology of West Africa is varied and complex. For the scale of this study geologically West Africa can be characterized by ancient (≤2.5Ga) Pre-Cambrian continental cratons, such as the West African Craton (WAC) and the Congo Craton (CC) (Figure 2). The cratons are separated by younger Cambrian (~500Ma) mountain belts, such as the Akwapim Hills in Ghana, which formed during the Pan African orogeny. By the early Cretaceous (~100-130Ma), the African continent had separated from the South American continent along the Mid-Atlantic spreading ridge (Figure 1). This period of intense tectonic and thermal activity was contemporaneous with the formation of various basins (such as the Bida and
Volta Basins, Figure 2); failed rift zones, such as the Benue Trough in Nigeria (Figure 2), and igneous intrusions, all of which exist within the African continent. Following this last major period of thermal and tectonic activity, the African continent had formed and the Atlantic margin of West Africa stabilised forming the passive continental margin.

The region, therefore, contains ubiquitous pre-existing structures that extend great lengths (up to hundreds of kilometers) within the continental and the oceanic crust (e.g. Neve et al. 1982). The main trends of these ancient structures are approximately E-W, related to the opening of the Atlantic Ocean, for example, in the ocean, the transform faults of the East Atlantic Fracture Zone (EAFZ), which include from north to south the St Paul’s, Romanche, Chain and Charcot Fracture Zones, and on the continent, the Central African Shear Zone (CASZ, Figure 2); and N-S, where younger weaker continental crust has deformed along the margins of older, stronger cratons, for example the Akwapim Hills and Pan African Suture Zone (Figure 2). Other structures that are oblique (trend NW-SE and NE-SW) to these major trends also exist, these features have often resulted where structures that accommodated E-W motion from the Atlantic spreading ridge terminate within the continent, e.g. the Benue Trough (Figure 2). Or for example, where the oceanic transform faults intersect with the continental margin forming extensional pull-apart basins such as the Ivory Coast and Dahomey basins (e.g. Burke, 1969; Antobreh et al. 2009; Figure 2).

In the eastern part of the study area, the CVL is volcanically and seismically active offshore and onshore. It is characterised by a SSW-NNE alignment of Tertiary to Holocene volcanoes and faults (Figures 1 and 2). The ‘Line’ extends ~2,000 km, from the East Atlantic Ocean in the SSW to the northern Cameroon in the NNW (Figure 2). Mt. Cameroon, ~65 km west of Douala (Figure 1 and 2), is the most volcanically and seismically active site with recent swarms of small magnitude events related to ongoing volcanic activity (e.g. Tabod et al. 1992). The ongoing volcanism and seismic activity of the CVL is thought to be associated with mantle upwelling and crustal uplift (e.g. Meyers et al. 1998).

Of importance to the seismic hazard potential of the region is the presence of thick ancient continental crust, ancient continental cratons, and the great length of pre-existing structures. The great strength of some of the ancient continental material is associated with lower crustal earthquakes and larger elastic thickness than in younger continental lithosphere (e.g. Sloan et al. 2011). The implication of this is that long faults with a large down-dip width in thick seismogenic crust have a higher maximum magnitude potential (with M greater than 7) than in younger relatively thinner more seismically active continental crust elsewhere. Additionally, the boundaries of continental cratons in slowly deforming regions elsewhere in the world are known to concentrate (tectonic) stresses, irrespective of how low they may be (e.g. Sykes, 1978). For all of these reasons, the potential earthquake hazard in West Africa is more significant than in a more seismically active region that does not contain these features.

3. EARTHQUAKE CATALOGUE

The earthquake catalogue compiled for this study covers the area between 10°W 15°E and 5°S 15°N (Figure 1) for the period 1615 to 2016. The dominant source of historical earthquakes is from Ambroseys and Adams (1986). This reference provides the first published critical compilation of historically documented earthquakes (including reports of the structural damage, felt shaking intensity, and estimates of earthquake isoseismals), in addition to the earliest available instrumental recordings. Instrumental seismicity for the region is from global earthquake catalogues and recent publications as shown in Table 1.

The different catalogues have been merged and duplicate events have been removed. The initial catalogue (without duplicates) consisted of 207 events. Foreshocks and aftershocks have been removed using the method of Gardner and Knopoff (1974), resulting in a final catalogue of 150 events. There are 14 mainshocks with $M_w \geq 5.5$, the epicentral locations of which are shown on Figure 1. All magnitudes are reported as moment magnitude ($M_w$). In the absence of enough duplicate earthquake data to generate correlations between local magnitude ($M_L$) and $M_w$ or body wave magnitude ($M_b$) and $M_w$, the various different types of reported magnitudes were converted to moment magnitudes using the empirically
derived relationships of Grünthal et al. (2009), which were developed from a database of earthquakes from central, northern, and northwestern Europe. These relationships have also been applied to the recent earthquake catalogue compiled by Musson (2014) for Ghana. In terms of tectonic history and geology, these areas of Europe are also a SCR and therefore broadly similar to West Africa. Therefore the Grünthal et al. (2009) magnitude conversions are considered appropriate in lieu of local data.

Table 1. Sources used to compile the updated earthquake catalogue.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Period Covered</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambraseys and Adams (1986)</td>
<td>1614-1984</td>
<td>Catalogue compiled based on the review of documented historical reports of felt shaking and damage. Isoseismals are estimated for the larger events.</td>
</tr>
<tr>
<td>Johnston et al. (1994)</td>
<td>1615-2003</td>
<td>Reassessment of historical and early instrumental earthquake data in terms of magnitude and location where possible.</td>
</tr>
<tr>
<td>International Seismological Centre (ISC) catalogue</td>
<td>1900-2016</td>
<td>Hypocentre location algorithm by Bondar and Storchak (2011). From 2011 to 2013 the seismic events are not reviewed in the catalogue.</td>
</tr>
<tr>
<td>National Earthquake Information Centre (USGS/NEIC)</td>
<td>1900-2016</td>
<td>Preliminary earthquake data from the United States Geological Survey (USGS). Source of most recent events.</td>
</tr>
<tr>
<td>Musson (2014)</td>
<td>1615-2009</td>
<td>The historical earthquake data for West Africa is mainly from Ambraseys and Adams (1986), updated to 2009 with ISC and NEIC earthquake data.</td>
</tr>
</tbody>
</table>

The largest and most damaging earthquakes have been reported from southern Ghana in the last two centuries (e.g. Ambraseys and Adams, 1986). Of these the July 1862, November 1906, and June 1939 earthquakes have been the most damaging. Some of the key seismological characteristics of these events have been summarised from Ambraseys and Adams (1986), they include: (i) ground shaking perceived over great areas, the 1862 event, for example, was felt up to 1,200km inland and for around 260km along the coast; (ii) reports of liquefaction in the lagoons and coastal regions; (iii) potential for intense foreshocks, the 1862 earthquake, for example, was preceded by six weeks of strong foreshocks, (iv) potential for ground surface rupture, the 1939 event was associated with up to 40cm of normal faulting offset at the ground surface; (v) potential for significant coastal inundation following the mainshocks, with reported water depths of up to a few tens of metres encroaching the coast.

5. ACTIVE FAULTS

A number of authors have discussed active faults in West Africa (Junner, 1914; Burke, 1969; Bondesen and Smit, 1972; Blundell, 1976; Bacon and Quaah, 1981; Ambraseys and Adams, 1986; Skobelev et al. 2004; Attoh et al. 2005; Akpan and Yakuba, 2010; Amonsah et al. 2012; Musson, 2014). Those that are considered active include the Ivory Coast Fault (offshore Côte d'Ivoire), Ivory Coast-Ghana Ridge Fault (or Coastal Boundary Fault, offshore of southern Ghana), the Akwapim Fault(s) in south-central Ghana, and Benin Faults (as inferred from the mapping by Ambraseys and Adams 1986; shown on Figure 2). The mapped faults in southern Ghana are the inferred sources of the largest historical events in this region. The NNE-SSW Ifewara Fault in Nigeria (Figure 2) may also be reactivated and associated
with small magnitude events felt in Nigeria (Akpan and Yakubu 2010).

In particular, studies have also focused on the potential connection between the long pre-existing E-W oceanic and the long pre-existing N-S and E-W continental structures that seem to intersect or merge at the continental margin (e.g. Burke, 1969; Blundell, 1976; Sykes, 1978; Ambraseys and Adams, 1986; Attoh et al. 2005). This is important, since if both the oceanic and continental structures are reactivated and connected then the potential maximum magnitude earthquake, particularly in thick continental crust (Section 2), will be larger than if either are considered separately. Currently, it is believed that the active Coastal Boundary Fault and Romanche Fracture Zone intersect at the continental margin of southern Ghana, and both are inferred to be active at least at the margin in southern Ghana. As suggested by Sykes (1978), it is possible that the same type of relationship exists for a number of the other Atlantic Fracture Zones that extend towards the continental margin of West Africa (Figure 2). Until further field and geophysical studies investigate these possible fault connections, however, this suggestion is speculative, but important to quantify for the above reasons. It is possible that reactivated structures in these other parts of the study area, such as the Atlantic margin of the Côte d'Ivoire and Nigeria (Figure 2), are analogous to the Ghana margin, but that the structures in these regions are either not active, or they have return periods that are much longer (thousands of years) than the documented historical earthquake record.

Figure 2. Geology and tectonic structure after Wright et al. (1985); Ambraseys and Adams (1986); Sykes et al. (1978); and mapped faults from the literature (Ambraseys and Adams, 1986; Akpan and Yakubu, 2010). *faults reported to be active in recent times as inferred from the literature not from this study.
Identifying the field evidence for active faulting, such as pre-historical earthquake surface ruptures and faults with well-preserved Quaternary scarps <10,000 years before present (BP), in slowly deforming regions is challenging. Often this is because the repeat times of significant surface-rupturing earthquakes are longer than the rates of erosion and deposition that erase this evidence that would otherwise be preserved in the landscape. In any case, further work (paleoseismological, remote sensing and field mapping) is required in order to better understand active faulting in West Africa. Specifically, it is important to understand whether the seismicity is dominated by relatively frequent small-magnitude earthquakes on small faults (that do not produce surface ruptures), or by large-magnitude earthquakes on long faults that generate surface ruptures but that have long return periods.

6. SEISMIC SOURCE MODEL

6.1 Area Sources

This paper has focused on developing area sources for seismicity in order to provide a reasonable updated framework within which to understand the earthquake hazard of the region. Future models can be updated to include fault sources with appropriate magnitude-recurrence relationships, if and when further information about the dominant fault locations and seismotectonic characteristics become available from published remote-sensing and field investigations. The seismic area source model developed for this study is presented in Figure 3. Eight area sources have been defined based on the different characteristic geology and tectonics in each area, and are described in detail below. The proposed maximum magnitude ($M_{\text{max}}$) earthquake for each area source has been estimated based on either the $M_{\text{max}}$ reported from regions of analogous geological/tectonic that are more seismically active with longer more complete earthquake records, or in the absence of such data, from observations of the length of pre-existing structures that can be observed in satellite imagery and digital topography, along with estimates of the crustal thickness.

6.1.4 Ghana Margin (1), extended continental crust

The Ghana margin overlies the transition between non-extended continental crust to the north and extended oceanic crust of the East Atlantic Fracture Zone to the south. For this reason, the Ghana Margin area source is similar to the Niger and Benin-Niger Margin source zones, however, the Ghana Margin differs from these two latter source zones in that: (i) faults in southern Ghana, such as the Coastal Boundary Fault, are active and have generated earthquakes with magnitude $\geq 5.5$ in the recent recent historical past (see Section 3), (ii) structurally, the Coastal Boundary Fault intersects and interacts with the Romanche Fracture Zone. This fault connection increases the potential maximum earthquake magnitude if an event was to rupture both segments of the onshore and offshore structures; (iii) the structures in this source have close proximity to the WAC, and with the greater crustal thicknesses associated with the edges of cratons, increasing the maximum magnitude potential of a given fault; (iv) the boundaries of continental cratons are known to concentrate even distant tectonic stresses. Based on the magnitudes of the documented historical events, on the remotely observed length of the pre-existing structures and on the proximity of the southern Ghana margin to the boundary of the WAC, the range of maximum magnitude considered for this source is between $M_w 6.5$ and 7.5, with a proposed maximum of $M_w 7.0$.

6.1.2 Benin-Niger Margin (2), extended continental crust

The Benin-Niger Margin source zone is underlain by extended continental crust that is transitional between the non-extended continental crust of Stable Continental Africa and the non-extended oceanic crust of the Atlantic Ocean basin (Figure 3). The most recent major tectonic activity to effect this region was Triassic extensional and lateral faulting and volcanism associated with the opening of the Atlantic Ocean basin. The compiled earthquake catalogue indicates very low rates of seismicity in this source zone, with an observed maximum magnitude $M_w 4.5$ in 2009 (Figure 3). The global earthquake catalogue for SCRs compiled by Johnston et al. (1994), however, indicates that regions of extended crust
associated with passive margins can generate earthquake with magnitude of up to $7.7\pm0.2$, therefore, the proposed $M_{\text{max}}$ of this source zone is $M_w 7.5$.

6.1.5 Niger Delta (3), extended continental crust

The Niger Delta source zone includes the south-western extent of the Benue Trough and approximately with the northern boundary of the Cameroon Volcanic Line (Figure 2). This SW extent of the Benue Trough is a basin formed within extended Precambrian continental crust and non-extended oceanic crust, overlain by up to 12km thickness delta sediments. Since this source zone contains an extended continental crust (represented by the SW termination of the Benue Trough), the maximum magnitude potential is greater than a conventional passive margin. For this region the estimated maximum magnitude range is between $M_w 6.5$ and 7.5, with a proposed $M_{\text{max}}$ of 7.5.

Figure 3. Seismic area source model developed for this study. Cities shown are the same as in Figure 1. Area sources: 1-3 extended continental crust; 4 non-extended continental crust; 5 and 6 volcanic; 7 non-extended oceanic crust, and 8 mostly non-extended continental crust.

6.1.1 Akwapim Fault Zone (4), non-extended continental crust

The Akwapim Fault Zone contains the Akwapim Hills, which reach 700m above the surrounding plains and Volta Basin and are formed of tightly folded metasedimentary and metavolcanic rocks. As discussed in Section 5, several authors have suggested geomorphological evidence for more recent
active faulting in this region, in addition to the apparent connection of this fault zone with the long oceanic transform faults at the continental margin of southern Ghana. The observed maximum magnitude from the compiled catalogue is $M_w$ 5.7 (Figure 3). However, the Johnston et al. (1994) earthquake catalogue indicates that earthquakes in Paleozoic-Mesozoic folded mountain belts formed of non-extended continental crust have magnitudes of up to 6.4±0.2. The proposed $M_{\text{max}}$ of this area source is 6.4.

6.1.3 Cameroon Volcanic Line Onshore (5), volcanic

The onshore CVL area source consists of continental crust and is therefore considered separately to the offshore CVL, which consists of oceanic crust. The largest earthquakes in the compiled catalogue for this source have magnitude 5.8 (Figure 3). Global studies of earthquakes associated with extensionally volcanically active regions have indicated that earthquake magnitudes in these regions are systematically lower than in non-volcanic regions (e.g. Smith et al. 1996). Using normal-fault surface length, width (down-dip extent), and rupture area, the Smith et al. (1996) study estimates a conservative maximum earthquake of $M_w$ 5.5 for such regions, which is roughly consistent with the observed seismicity from the compiled catalogue. In the south of the onshore CVL source zone, however, the crustal thickness increases with proximity to the Congo Craton (Noel et al. 2014). Assuming that this increase in the crustal thickness also coincides with an increase in the seismogenic thickness (see Section 2) and given that the length of structures that can be identified in satellite imagery exceeds several tens of kilometres, a more conservative $M_{\text{max}}$ 6.0 has been adopted for this source.

6.1.3 Cameroon Volcanic Line Offshore (6), volcanic

The CVL offshore source zone consists of oceanic crust that is relatively much younger than the continental crust (between around 120 to 55Ma, with age increasing to the east). The majority of instrumentally recorded events in the compiled catalogue range from magnitude 2.5 to 5.5, this is consistent with the magnitude range of other volcanically active intraplate oceanic settings worldwide (Smith et al. 1996). In 1967 five earthquakes of magnitude 5.0 and 5.5 were recorded in the ISC catalogue at different locations (Figure 3). Since the oceanic section of the CVL consists of relatively younger, relatively thinner crust, by contrast to the onshore continental CVL, and additionally does not lie in close proximity to the Congo Craton, the proposed $M_{\text{max}}$ is 5.5.

6.1.6 Continental Background Seismicity (7), predominantly non-extended continental crust

The Continental Background Seismicity area source consists of predominantly of non-extended continental crust greater than at least 500Ma, with lesser regions of extended crust that are transitional between the non-extended continental crust of stable continental Africa and the non-extended oceanic crust of the Atlantic Ocean Basin. These latter regions are represented by the passive margin regions of southern Gabon and southern Cote d’Ivoire. Several major structural features exist within this source zone, including the Benue Trough (extended continental crust), Pan African Suture, and the Central African Shear Zone (CASZ). These different structural domains exist within a single area source because in terms of distribution of seismicity there is no reason to subdivide them from the background source (Figure 3). Such structures, however, do influence the maximum potential earthquake magnitude. Although the maximum earthquake magnitude in the compiled catalogue has $M_w$ 6.1 (southeast Cameroon in 1945; Figures 1 and 3), the global earthquake catalogue of SCR (Johnston et al. 1994) indicates that some of the world’s largest earthquakes $M_w$≥8 have occurred in non-extended and extended SCR crust. For this reason, the proposed $M_{\text{max}}$ in this area source is 8.0.

6.1.7 Oceanic Background Seismicity (8), non-extended oceanic

The Oceanic Background Seismicity area source contains non-extended oceanic crust (generally $\geq$55Ma) of the Nubian (African) plate and is located thousands of kilometers east of the active Mid-Atlantic Ridge (MAR) spreading center. In the north, this source contains the East Atlantic Fracture Zone (EAFZ). This source is characterised by low rates of seismicity, which is a characteristic feature
of other similar oceanic settings worldwide (Okal, 1983). Larger events up to $M_w$ 7.0 are rare, and have been associated with regions of extended crust (e.g. along the continental margins of North America) or are located within ~500 km of an active plate boundary. The largest earthquake in the compiled catalogue was a magnitude $M_w$ 6.3 event in 1971 (Figures 1 and 3). We consider a range of maximum earthquake magnitudes between $M_w$ 6.6 and 7.2 based on $M_{max}$ observations of global (spreading ridge and) transform faults after Bird et al. (1992). The earthquake data compiled by Bird et al. (1992) also indicate that the $M_{max}$ increases with decreasing rates of deformation. Since rates of deformation are very low ($\leq$2mm/year) in this region (Deprez et al. 2013) the proposed maximum magnitude estimated for this source is 7.0.

7. PRELIMINARY PROBABILISTIC SEISMIC HAZARD MODEL (PSHA) FOR WEST AFRICA

A preliminary PSHA has been carried out for West Africa, based on the presented earthquake catalogue, with duplicates, fore- and aftershocks removed (as described in Section 3), and seismic source model. In this preliminary assessment no fault has been included. The following inputs need to be defined: the depth distribution of the earthquake hypocenters, the magnitude recurrence relationships and the ground motion prediction equations (GMPEs).

For the earthquake depth distribution, statistics based on the actual catalogue are not realistic, since too few earthquakes have well-constrained depths, for example determined by body-waveform modeling. The earthquake depth distribution has been informed from the literature. We use the earthquake depth distribution determined for the western branch of the East African Rift system (Craig et al. 2011), which although obviously more seismically active, has a similar geology and tectonic history to West Africa. Within estimated 40km thick stable continental crust, it is estimated that approximately 30% of earthquakes occur in the upper 10km of the crust, 30% of events occur between 10 and 20km depth, 25% of events occur between 20 and 30km depth and the final 15% of events occur between 30 and 40km depth. This proposed depth distribution includes allowance for the proposed shallow depths (8-15km) of the coastal seismicity determined for West Africa by Suleiman et al. (1993).

The observed seismicity is used to determine the earthquake-recurrence relationships for each area source (described in Section 6) assuming that: (i) the temporal behavior of the seismicity can be approximated with a Poissonian distribution; and (ii) the magnitude distribution of seismicity is represented by the truncated Gutenberg and Richter (1954), G-R power law model. As a first step the catalogue completeness need to be determined. Since the final catalogue has relatively few events (150) it is difficult to assess the completeness thresholds using standard statistical methods (e.g. Stepp, 1972). For this study the completeness thresholds of Johnston et al. (1994) for Central and West Africa have been applied, with $M>4$ complete from 1964, and $M>5.5$ complete from 1950.

The minimum magnitude threshold for both the computation of the G-R parameters and for the PSHA calculations, $M_{min}$, has been considered equal to 4. This value has been chosen to retain a larger number of earthquakes in the statistical computations. Given the scarcity of earthquake data, the parameters of the G-R relationships have been captured using the penalized maximum likelihood (Veneziano and Van Dyke, 1985) regression method. A priori $b$-value of 0.8 with a weighting of 20% has been assumed for these analyses. Uncertainty on both the activity rate and the $b$-value of the curves ($\nu$ and $b$, respectively) has been included in a logic tree approach. An example of the G-R relationship for the entire catalogue is shown in Figure 4, with a mean $b$-value of 0.6. This value is less than what found at a global scale by Kagan et al. (2010), where a $b$-value of 0.96±0.15 was obtained for plate interiors. A sensitivity has been carried out using a minimum threshold magnitude of 5, consistently with Kagan et al. (2010). A $b$-value of 0.96 ± 0.22 has been obtained. In a more detailed PSHA, a sensitivity analysis on the effect of these assumptions on the final seismic hazard results should be carried out and if necessary this uncertainty should be included in a logic tree approach. Past experience suggests that the use of a higher minimum magnitude leads to underestimation of seismic hazard at low return periods in region of low-to-moderate seismicity. Epistemic uncertainty on the maximum magnitude has also been considered by adopting the proposed $M_{max}$ values for each area source, described in Section 6, as mean maximum
magnitude and adding an uncertainty of plus and minus 0.3 Mw. Sensitivity analyses on the Mmax value adopted in the Gutenberg-Richter relationships showed that it has little impact on the final ν and b parameters when their uncertainty is considered.

No regional GMPEs have been developed for West Africa and recorded ground motion data are not currently available for the study area, therefore, the preliminary selection of the GMPEs is based on available models from other regions with the same seismotectonic context (Cotton et al. 2006; Bommer et al. 2010). The models of Atkinson and Boore (2006), AB06, and Pezeshki et al. (2011), PEA11, have been preliminarily selected. Both equations have been developed for SCR tectonic regimes, using the fundamental earthquake databases of Eastern North America (ENA), and for hard-rock site conditions (Vs30≥2000 m/s). In the absence of more detailed descriptions of the attenuation of ground motion in the region, the two models are equally weighted in the logic tree.

7.1 Results

Mean hazard curves for six of the most populated cities in West Africa are shown in Figure 5. The preliminary results indicate that the range of PGA for the 475 year return period is between about 0.05g (Accra and Porto Novo) and about 0.06g (Lome). For the 2475 year return period the PGA ranges from 0.08g (at Duala and Guinea Bata) to 0.15g (at Accra and Lome).
6. SUMMARY AND RECOMMENDATIONS

There are some key geological and seismotectonic features in West Africa that increase the earthquake hazard potential of the region relative to more seismically active regions elsewhere that do not contain these features, including: 1) the length of pre-existing faults that have the potential for reactivation in spite of very low deformation rates; 2) the significant seismogenic thickness (up to 40km) of ancient continental crust, which increases the maximum magnitude potential of an earthquake on any given fault; and, 3) the presence of continental cratons, the boundaries of which are known to concentrate tectonic stresses.

A number of potential seismological characteristics of moderate earthquakes in southern Ghana have also been highlighted for future hazard studies considering seismic design, including: potential for liquefaction particularly surrounding coastal regions, widespread large ground motions due to lack of seismic attenuation in ancient thick lithosphere, strong foreshock and aftershock sequences, ground surface rupture, potential for coastal inundation.

Though identifying active faults in the landscape of slowly deforming regions is challenging, such work is important, particularly in regions where the documented historical record is relatively short, such as West Africa. Therefore, the results of this study should not be used for design purposes until these further studies are completed.

9. REFERENCES


