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# Studies of crustal structure, seismic precursors to volcanic eruptions and earthquake hazard in the eastern provinces of the Democratic Republic of Congo

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ABSTRACT

In recent decades, civil wars in the eastern provinces of the Democratic Republic of Congo have caused massive social disruptions, which have been exacerbated by volcanic and earthquake disasters. Seismic data were gathered and analysed as part of an effort to monitor the volcanoes and quantitatively assess the earthquake hazard. This information can be used to regulate the settlement of displaced people and to "build back better". In order to investigate volcanic processes in the Virunga area, a local seismic velocity model was derived and used to relocate earthquake hypocenters. It was found that swarm-type seismicity, composed mainly of long-period earthquakes, preceded both the 2004 and 2006 eruptions of Nyamuragira. A steady increase in seismicity was observed to commence ten or eleven months prior to the eruption, which is attributed to the movement of magma in a deep conduit. In the last stage (1 or 2 months) before the eruption, the hypocenters of long-period earthquakes became shallower. Seismic hazard maps were prepared for the DRC using a 90-year catalogue compiled for homogeneous $M_w$ magnitudes, various published attenuation relations, and the EZ-Frisk software package. The highest levels of seismic hazard were found in the Lake Tanganyika Rift seismic zone, where peak ground accelerations (PGA) in excess of 0.32 g, 0.22 g and 0.16 g are expected to occur with 2%, 5% and 10% chance of exceedance in 50 years, respectively.



## 1. Introduction

In recent decades the inhabitants of the eastern provinces of the Democratic Republic of the Congo (DRC) have experienced a series of coupled human-induced and natural disasters. Civil wars in the DRC and neighbouring countries have created waves of roaming militias and refugees, damaged the infrastructure, weakened governance, and disrupted economic activities and social services. The situation has been exacerbated by volcanic eruptions and earthquakes. Population movement and growth has led to uncontrolled settlement in regions that are exposed to earthquake and volcanic hazards. For these reasons, a revised assessment of seismic and volcanic hazard is urgently needed. In this paper we describe efforts to gather data and derive models of geological processes that can be used to monitor volcanoes and assess the earthquake hazard, plan the settlement of displaced people, and to "build back better".

## 2. Risks posed by earthquakes and volcanic eruptions

Earthquakes pose a significant risk to the eastern provinces of the DRC. The Western Rift Valley of Africa has experienced several severe earthquakes ($M \geqslant 6$) in recent historical times that have caused loss of life and damage to property (Figs. 1 and 6). For example, the central part of Lake Kivu experienced a large earthquake ($M_w$ 6.2) on 24 October 2002, which was felt strongly at Goma, Bukavu and Kigali (Mavonga, 2007a). On 3 February 2008 an $M_w$ 6.0 earthquake occurred 20 km north of Bukavu City, claimed 9 lives, seriously injured more than 400 people, and caused about 1500 houses to collapse. While the seismic hazard in the Great Lakes region has previously been assessed by Midzi et al. (1999), Twesigomwe (1997) and Zana et al. (1992), social conditions in the region are continually changing, and seismic hazard is generally not taken into account in land-use planning. Our new seismic hazard assessment makes use of the new strong motion attenuation equation developed by Mavonga (2007b), based on digital seismic records of events from seismic stations in the Western Rift Valley of Africa, and takes local details of geology, tectonics and recent seismicity into account.

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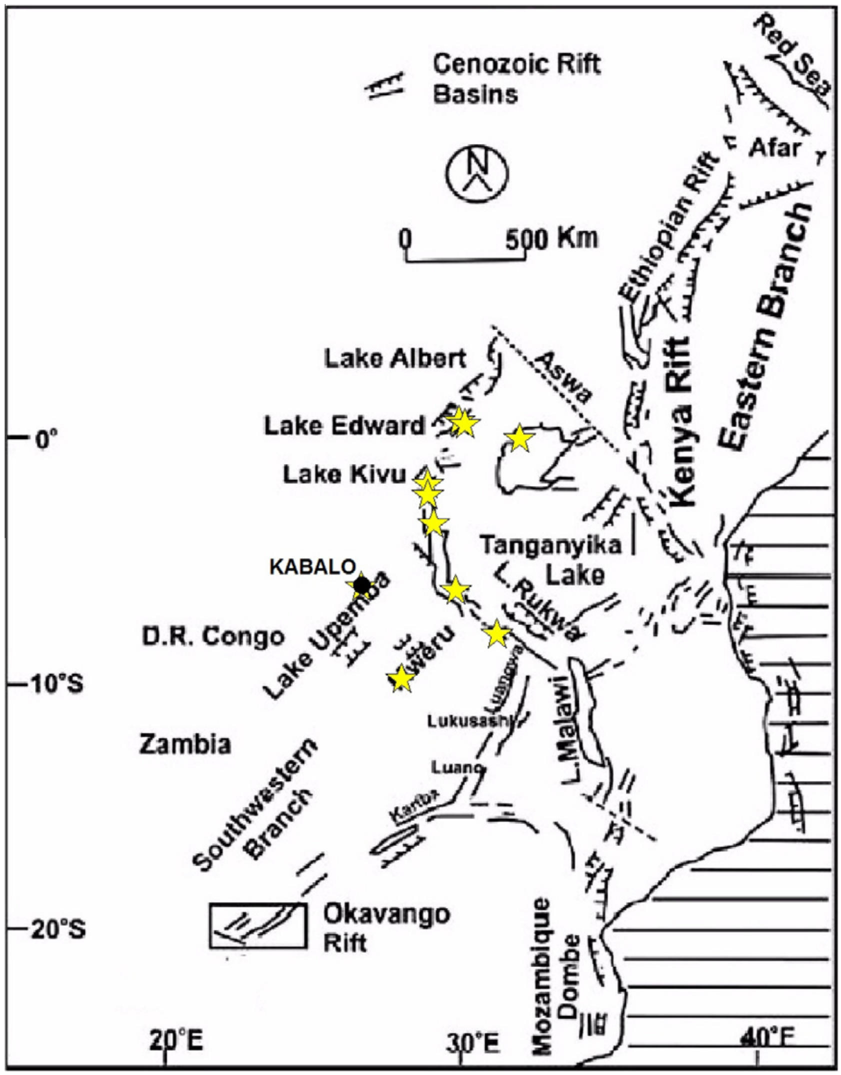


**Fig. 1.** Schematic map of the East African Rift system showing the continental break-up in the southeast of the DRC and northern Zambia (modified from Kinabo et al. (2007)). The epicentres of earthquakes with $M \geqslant 6$ occurring since 1910 in the Western Rift Valley are indicated by stars.

Volcanic eruptions also pose a significant risk. The Virunga volcano group, which is located at the northern edge of Lake Kivu, consists of eight major volcanoes (Fig. 2). The westernmost volcanoes, Nyiragongo and Nyamuragira, have been the most active in the past century. Nyamuragira has exhibited two types of eruptive activity: lava lake activity in the summit caldera from 1921 to 1938; and flank eruptions that issue lava through the opening of new fissures. Nyiragongo, about 18 km north of Lake Kivu and the city of Goma, has been active since 1884. Its eruptive activity is characterized by the appearance of a lava lake in the summit crater due to intermittent short pulses of magma. It had a lava lake in the summit crater from 1928 to 1977. Nyiragongo volcano erupted suddenly on 10 January 1977. Approximately $22 \times 10^6$ m$^3$ of extremely fluid lava issued from flank fissures and flowed down the slope at up to 60 km/h, killing about 70 people and reaching within 600 m of Goma airport. Nyiragongo erupted again on 17 January 2002. About $20 \times 10^6$ m$^3$ of lava issued from the central crater and at several points along a system of fractures that rapidly developed along the entire southern flank of the volcano. Two main flows entered the town and caused major devastation, forcing the rapid exodus of 300,000–400,000 people. About 15% of the surface of the town was affected, including parts of the airport, most of the business centre, and the dwellings of 120,000 people. An estimated 150 people died as a consequence of eruption.

## 3. Determination of crustal seismic velocity structure

Seismicity prior to the eruptions of Nyamurigira in 2004 and 2006 was studied to determine if there were any precursory signatures that might be used to give early warning of future eruptions. In order to map the migration of hypocenters of earthquakes accurately and reveal trends that could be precursors of eruptions, a new model of the local crustal seismic velocity model for the Virunga area was derived (Tuluka, in press). This model was applied to the determination of hypocentres during the period prior to the 27 November 2006 Nyamuragira eruption (Mavonga et al., in press).

In the receiver function technique, teleseismic body waveforms are used to image the crustal structure beneath isolated seismic stations. These waveforms contain information related to the source time-function, structure of the mantle, and the local crustal structure beneath the recording site. The receiver function is obtained by removing the effects of the source and mantle path.

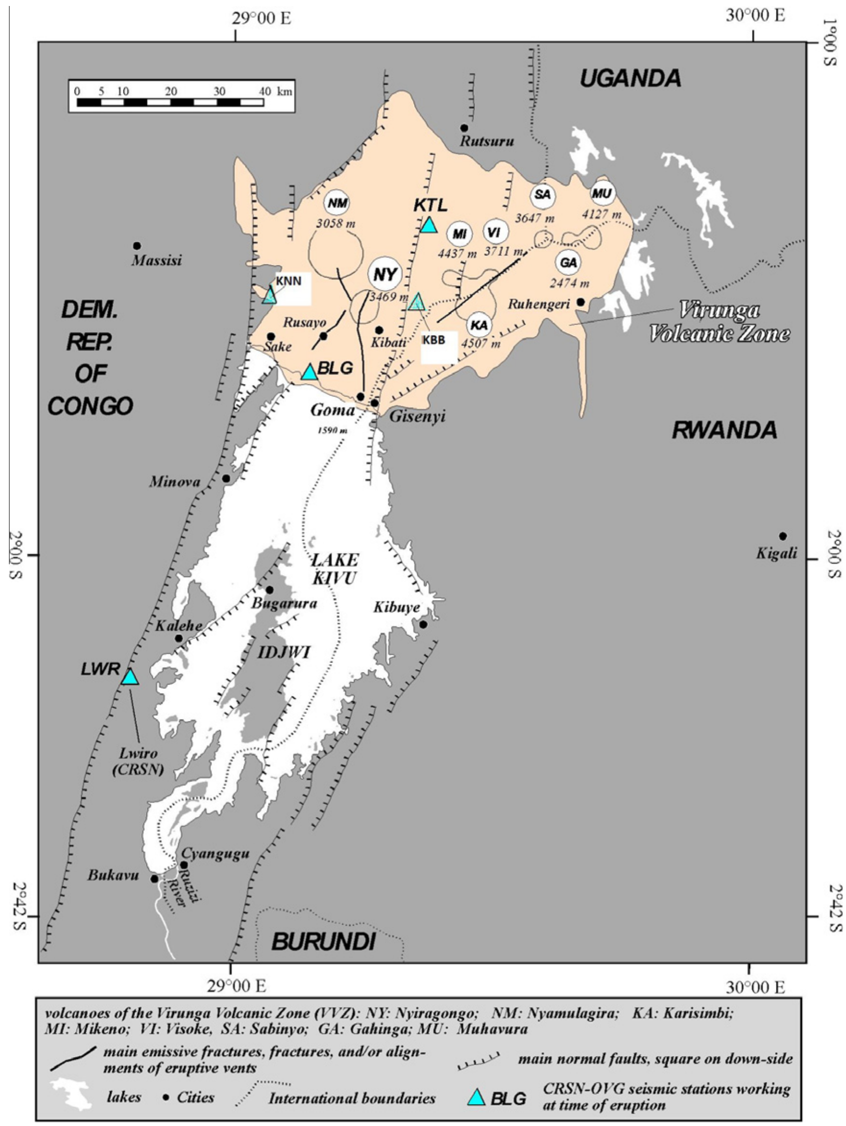


**Fig. 2.** Map showing the eight volcanoes of the Virunga Volcanic Field and seismicity of Lake Kivu and surrounding area for the period 1976–2002. (NY = Nyiragongo; NM = Nyamuragira; KA = Karisimbi; MI = Mikeno; VI = Visoke; SA = Sabinyo; GA = Gahinga; MU = Muhavura). The filled triangles and squares indicate seismographic stations and earthquake epicentres, respectively. The filled small circles indicate cities (modified from Komorowski et al. (2003) and Mavonga (2007a)).

The receiver function method relies on the partial conversion of the P-wave to an S-wave at a discontinuity, in this case the Moho. The converted phase, called Ps, arrives at the station within the P-wave coda. As S-waves travel more slowly than the P-waves, the thickness of the crust can be calculated directly using the difference in the arrival times of the direct P-wave and the Ps phase if the velocity model is known. If the velocity model is unknown, the receiver function can be inverted to produce a model of the seismic velocity structure under a given seismic station. The method used in this study (Owens, 1984) incorporates minimum roughness constraints to address the non-uniqueness problem, and seeks to minimize the differences between observed and synthetic receiver functions. An important assumption of the time domain inversion technique is that the initial model must be close to the true Earth velocity structure (Ammon et al., 1990). Thus *a priori* information available for the area under investigation is helpful in constraining the solution.

Between May 2004 and December 2007 more than 100 teleseismic events were recorded at broadband stations KUNENE (KNN) and KIBUMBA (KBB), located 29 km apart on opposite sides of the Western Rift Valley in the Virunga area (Fig. 2). Forty-six earthquakes with magnitudes greater than 5.5, good signal-to-noise ratio and epicentral distances between 30° and 92° from the stations were chosen for the analysis. Several existing models of crustal structure in the East African Rift were used to derive three initial models: (i) the Nolet and Mueller (1982) model; (ii) the average of the Bram (1975), Bonjer et al. (1970), and Nolet and Mueller (1982) models, and (iii) a combination of (i) and (ii). The velocity models are shown in Fig. 3. The crust-mantle transition zone beneath the area sampled by KNN and KBB was determined to be at a depth from about 36 to 39 km and 30 to 41 km, respectively. A low-velocity zone was found beneath stations KNN and KBB at depths of 20–30 km and 18–28 km, respectively, and with average velocity 5.9 km/s and 6.0 km/s. This low-velocity zone could be caused by a magma chamber or a melt-rich sill. The models show also high velocity material (6.8–7.4 km/s) lying beneath stations KNN and KBB at depths of 3–20 km and 3–10 km, respectively, indicative of magma cumulates within the volcanic edifice.

The KNN and KBB velocity models were averaged to produce a simplified crustal model (Table 1) that was used to locate the hypocentres of volcanogenic earthquakes.

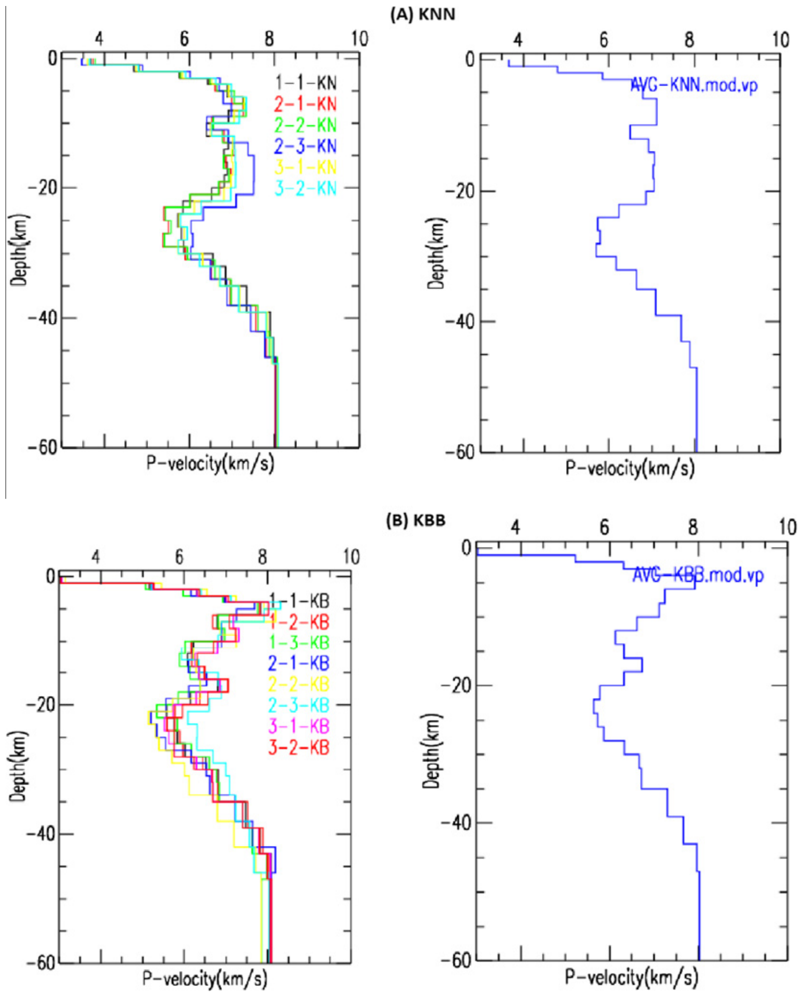


**Fig. 3.** Velocity models for the (A) KNN and (B) KBB stations. The same three initial models were used for both KNN and KBB. The models derived from the three initial models are shown on the left, and the average of the three models on the right.

**Table 1**
Average local velocity model in the Virunga area.

| *Vp* (km/s) | Top of the layer (km) |
|---|---|
| 5.40 | 0.0 |
| 6.40 | 4.0 |
| 6.85 | 32.0 |
| 7.69 | 39.0 |
| 7.96 | 43.0 |
| 8.00 | 47.0 |

## 4. Seismic precursors to volcanic eruptions

The movement of magma in the Earth's crust produces volcanogenic earthquakes, which are often classified into three types (Fehler and Chouet, 1982; Tanaka, 1983; McNutt, 1992 and Lukaya et al., 1992):

(1) "Short-period (SP) earthquakes", which have distinct P- and S-phases and dominant frequency greater than 5 Hz. SP events are believed to be induced by a brittle fracture of the roof rock under a stress due to magmatic pressure (Ohnaka and Mogi, 1982).
(2) "Long-period (LP) earthquakes", which are transient signals with a weak P-phase, an emergent or indistinct S-phase, and a dominant frequency between 1 and 3 Hz. LP events are probably due to the excitation of some fixed cavity under the volcano and/or the migration of magmatic fluid consisting of hot water and/or magma (Fehler and Chouet, 1982; Nishimura et al., 2002).
(3) "Volcanic tremors", a term used to describe the sustained occurrence of long-period events, which appear on a seismogram as an irregular sinusoid of far longer duration than a tectonic earthquake of the same amplitude.

Several studies of changes in the distribution of volcanogenic earthquakes in time and space prior to eruptions of volcanoes in the Virunga region have been carried out in efforts to identify signatures that could be used to provide early warnings of future eruptions. The main findings are summarized below.

### *4.1. Seismicity associated with the Nyiragongo eruption of January 17, 2002*

Nyiragongo erupted on 17 January 2002 after about 7 years of relative dormancy. Fluid lava poured out from several locations along a system of fractures that opened on the southern flank of the volcano. Kavotha et al. (2003) studied the seismic activity associated with the eruption, and found that precursory seismic activity commenced about 10 months before the eruption, were characterized by regular (almost daily) periods of volcanic tremor activity and swarms of long-period earthquakes. The eruption

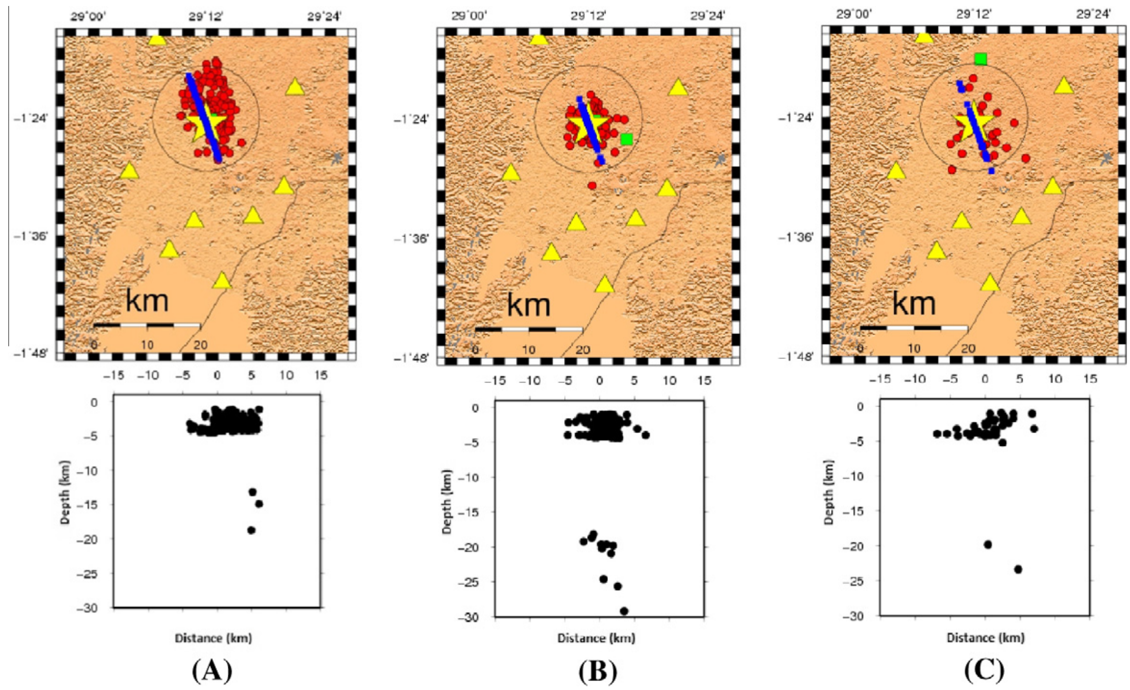


**Fig. 4.** Earthquake hypocentres observed in the Virunga area prior to the eruption of Nyamuragira on 27 November 2006. (A) 1 July 2004–01 August 2004, shortly after the previous eruption of Nyamuragira on 8 May 2004, 155 events. (B) 25 July 2006–25 August 2006, 141 events. (C) 28 October 2006–27 November 2006, 44 events. The circle defines the area used for the depth section within which epicentres are selected. Epicentres within the circle are projected normal onto the cross-section. The continuous blue line crossing the epicentres is the line of cross-section of earthquake hypocenters. It is defined by a centre marked by a large star (set at the summit of the Nyamuragira crater) and an azimuth (set to 160°). This direction coincides with that of the main fissure connecting the volcanoes Nyiragongo and Nyamuragira. The large filled triangles indicate seismic stations. The small filled circles and squares mark long and short-period events, respectively.

was followed by intense seismic activity: SP events were mainly clustered between Nyiragongo and the north shore of Lake Kivu, coinciding with the zone in which fractures opened during the eruption; while numerous LP earthquakes were concentrated in the Nyamuragira volcano field, and culminated in a new eruption of this volcano in July 2002.

### *4.2. Seismicity associated with the Nyamuragira eruptions of 8 May 2004 and 27 November 2006*

Nyamuragira volcano is characterized by frequent Hawaiian-type eruptions and highly potassic lavas (Hayashi et al., 1992). An active lava lake persisted in the summit crater from 1921 to 1938. Most eruptions, with the exception of the summit eruption of 1938, occurred on the flanks of the volcano. The most recent flank eruptions occurred on 27 January 2000, 5 February 2001, 25 July 2002, 8 May 2004 and 27 November 2006.

The seismicity in the Nyamuragira area in the interval between the 2002 and 2004 eruptions was studied by Mavonga et al. (2006). Several stages were identified:

(1) A period of relatively low seismic activity persisted for about a year following the July 2002 eruption. It was characterized by shallow LP earthquakes.
(2) About ten months prior the May 2004 eruption, a steady increase in deep LP earthquake activity was noted. These events were attributed to the movement of magma in a deep conduit.
(3) About 4 months prior to the May 2004 eruption, swarm-type seismicity composed mainly of LP earthquakes emerged. It was accompanied by tectonic seismicity related to rifting.
(4) About two months prior to the May 2004 eruption, the deep LP earthquake activity declined and the shallow LP earthquake activity increased.

The seismicity between the 2004 and 2006 eruptions was studied by Mavonga et al. (in press). The new velocity model (Tuluka, in press) was used to locate the hypocenters of these events, yielding better resolution. Fig. 4 shows the three stages of seismicity activity leading up to the 2006 eruptions.

(1) Seismicity following the 2004 eruption was dominated by the occurrence of shallow (0–5 km) LP events.
(2) About a year prior to the 2006 eruption, swarms composed mainly of LP events were observed. Both shallow (0–5 km) and deep (20–30 km) LP events were observed, separated by an aseismic zone. This aseismic zone is probably a region of low rigidity occupied partly by magma, similar to that detected by Hamaguchi (1983). The deep LP volcanic earthquakes may be attributed to a fairly steady flow of magma into the Nyamuragira shallow reservoir from a deep source located at about 20–30 km.
(3) About 1–2 months prior to the 200 eruption, the LP events clustered at a shallow depth. These events were probably associated with the filling of the shallow reservoir with magma to its threshold volume.

The new average velocity model (Tuluka, in press) was also used to determine the hypocenters of both SP and LP earthquakes with clear P-wave onsets that occurred in the day prior to the 2006 eruption (Fig. 5). The hypocenter maps were compared with InSAR data provided by National Museum of Natural History, Luxembourg (D'Oreye et al., 2007). The integrated study showed inflation of the crust along the axis of a fracture that links the two volcanoes, and subsidence of the crust to the east of Nyamuragira. The epicentres determined using the new local seismic velocity model show significantly better agreement with the locus of inflation and the eruption site than the epicentres that were determined using a regional seismic velocity model. In fact, the eruption site is situated

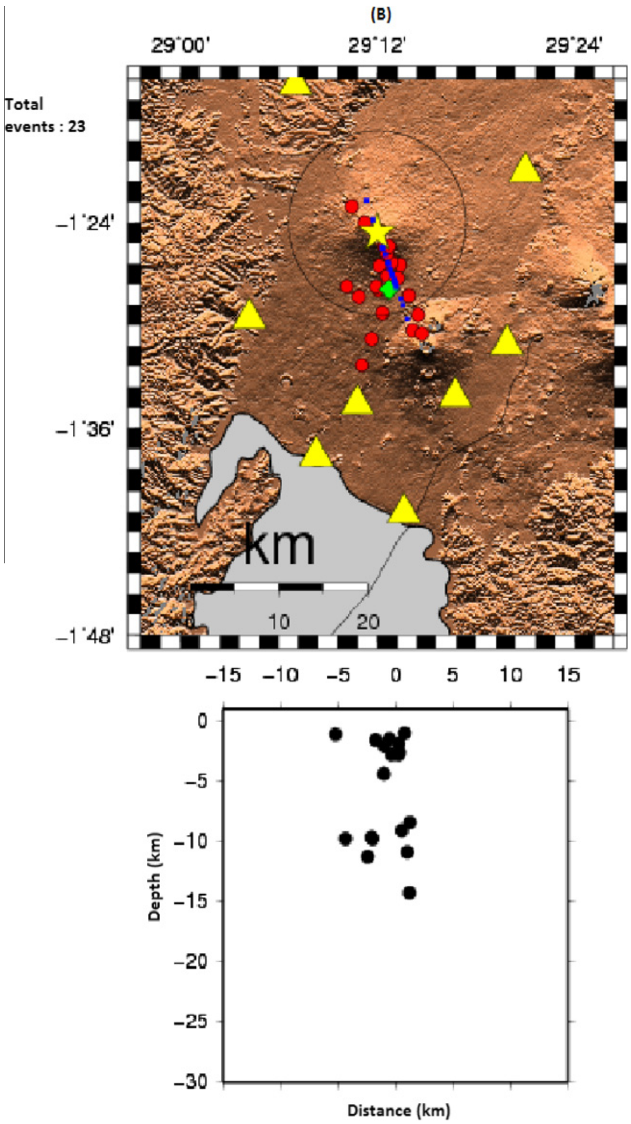


**Fig. 5.** Hypocenters of volcanogenic earthquakes (26 November 2006–27 November 2006) prior to the Nyamuragira eruption computed using a new local seismic velocity model. The lozenge marks the eruptive site. The other symbols are defined in the caption of Fig. 4.

at the intersection of two fractures, one linking the two volcanoes, and the other tangential to the southwest flank of Nyiragongo. Furthermore, these epicentres are distributed along a linear trend, which may be associated with the opening of fissures before eruption.

### 4.3. Precursory phenomena

In the year preceding the 2002 eruption of Nyiragongo and the 2004 and 2006 eruptions of Nyamuragira there was a progressive increase in number of LP earthquakes. These observations suggest that changes in the rate and location of long-period earthquakes, integrated with other available data (e.g. INSAR, GPS, geochemical, geological), may be used to characterize volcanic processes and forecast volcanic eruptions in the Virunga area.

## 5. Probabilistic seismic hazard assessment

A probabilistic approach (Cornell, 1968; McGuire, 1976 and McGuire, 1993) was used to map the seismic hazard in DRC and surrounding areas (Mavonga and Durrheim, 2009). Probabilistic seismic hazard analysis involves three main steps: definition of seismic source zones, determination of seismicity parameters for each source zone, and preparation of seismic hazard maps. The main steps are summarized below.

### 5.1. Data compilation

All available instrumental seismic data covering the region 14°S to 6°N and 10°E to 32°E for the period 1910–2008 were compiled in a catalogue homogenized according to the moment magnitude scale $M_w$ (Mavonga and Durrheim, 2009). All of the DRC, with the exception of the westernmost region, was included in the study area, together with parts of Uganda, Tanzania, Rwanda, Burundi, Sudan and Zambia.

A Poisson model of earthquake occurrence was adopted for this study (Bender and Perkins, 1987). The model assumes that events are independent. Therefore all foreshocks, aftershocks and earthquake swarms were removed from the initial catalogue of 2249 events. Furthermore, $M_w = 4$ was selected as the lower magnitude bound ($M_{min}$) because smaller earthquakes are considered unlikely to cause damage, even to houses that are poorly designed and built. Thus any remaining events with $M_w < 4$ were also excluded from the catalogue, leaving a sub-catalogue of 822 events.

### 5.2. Aftershock sequences

Aftershock studies can provide valuable information when assessing seismic hazard. Firstly, aftershocks must be identified so that they can be removed from the earthquake catalogue in order use standard methods to compute the seismic hazard. Secondly, aftershocks can be used to estimate the linear dimension of the rupture. Lastly, aftershocks can be used to characterize seismicity and contribute to the definition of seismic source zones.

The characteristics of several aftershock sequences in the Kivu province were studied by Mavonga (2007a). It was found that most of the aftershocks of the Ruwenzori earthquake (5 February 1994, Mb5.8) were located on the eastern flank of the main escarpment. The aftershocks of the Masisi earthquake (29 April 1995, Mb5.1) were confined to the northwest margin of Lake Kivu, where swarm-type earthquakes are normally observed. The Kalehe earthquake (24 October 2002, Mb5.9), which occurred in the central part of Lake Kivu, was the largest earthquake observed in the Lake Kivu basin since 1900.

It has been shown in the studies of aftershocks sequences (Utsu, 1957; Mogi, 1962; Page, 1968) that the number $N$ of earthquakes per day, above some given magnitude threshold, is usually expressed as a function of time as follows:

$$N = kt^{-p} \quad (1)$$

where $k$ is the rate of occurrence 1 day after the beginning of the sequence; and $t$ is the time after the main shock in days. The usual value of $p$ is close to 1 (Utsu, 1957). The $p$-value for Ruwenzori and Masisi earthquake was found to be about 0.6, quite similar to $p = 0.7 \pm 0.02$ found for the 1966 Ruwenzori earthquake sequence (Lahr and Pomeroy, 1970; Zana and Hamaguchi, 1978). The $p$-value of Uvira earthquake (Zana and Hamaguchi, 1978) and that of Kalehe are $0.92 \pm 0.17$ and 1.0, respectively, in agreement with values found in other geotectonic zones.

The spatial distribution of aftershocks may be used to estimate the linear dimensions of the fault-rupture. A statistical relationship

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between fault area and moment magnitude was established by (Mavonga, 2007a):

$$\log S = 0.3221M_w + 0.6058 \quad (2)$$

where S is the fault area (km$^2$) and $M_w$ is the moment magnitude.

### 5.3. Definition of potential seismic source zones

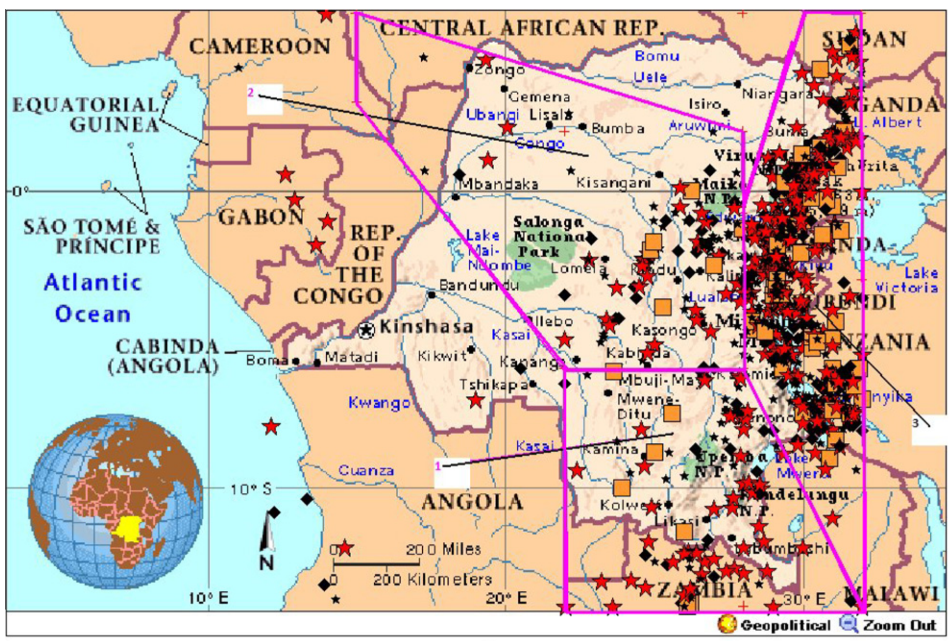
Seismic source zones are zones within which all available information may be averaged, and are usually associated with active geological or tectonic features such as faults. Based on previous studies of the tectonics and seismicity of the area, three seismic source zones were identified as the main producers of damaging earthquakes in the eastern provinces of the DRC and surrounding areas (Fig. 6).

#### 5.3.1. Upemba–Moero Rift

Sebagenzi and Kaputo (2002) reviewed the available gravity, heat flow and seismological data in the region, and found geophysical evidence for continental break-up in south-eastern DRC and north-western Zambia. The most prominent seismotectonic features in this region are the Upemba and Moero Rifts. The Upemba Rift may extend northward to the Kabalo area, which experienced an $M_w$ 6.5 earthquake on 11 September 1992 (Zana et al., 1992). However, the relationship between the surface structures and deeper features needs to be determined in order to establish whether the Upemba and Moero Rifts are, in fact, part of the Western Rift Valley (Sebagenzi and Kaputo, 2002).

#### 5.3.2. Congo basin

Studies of the focal mechanisms of four $M_b$5.4–$M_b$5.6 earthquakes that occurred in the Congo basin during the period 1976–

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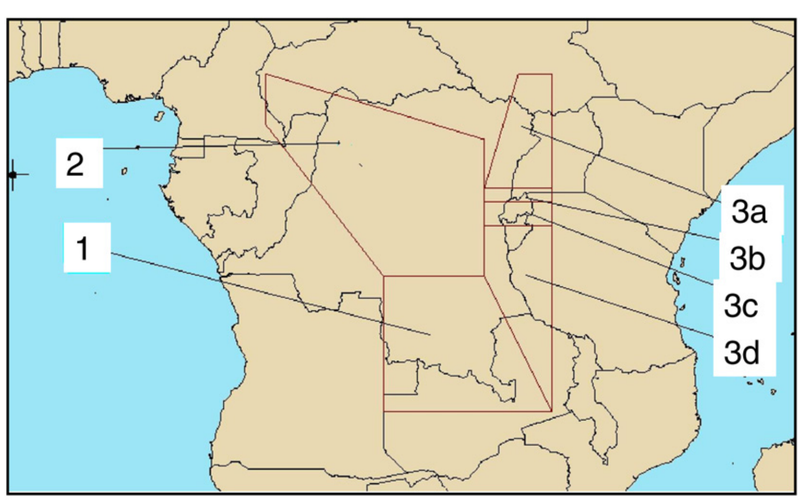


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**Fig. 6.** A. Earthquakes in the D. R. Congo and surrounding areas for the time period 1910–2007 used in the seismic hazard analysis. Symbols indicate earthquake magnitudes: small stars (4.0–4.2), lozenges (4.2–4.3), rectangles (4.3–4.4), and large stars (>4.4). B. Seismic source zones defined in this study: 1 = Upemba–Moero Rift; 2 = Congo Basin; 3 = Western Rift Valley, which is divided into four sub-zones 3a = Ruwenzori–Lake Edouard trough; 3b = Virunga volcanic complex–Rutsuru–Masisi; 3c = Lake Kivu Basin–Ngweshe–Ruzizi and 3d = Lake Tanganyika Rift.

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1998 demonstrated that the Congo basin is predominantly in a state of horizontal compression, which could be explained by ridge-push forces originating from the Mid-Atlantic Ridge and the East African Rift System (Fairhead and Stuart, 1985; Dziewonski et al., 1996; Atalay, 2002). No surface ruptures have been documented, even though some large and damaging shocks have occurred in that area.

### 5.3.3. Western Rift Valley of Africa (WRA)

Four seismic sub-zones were identified in the WRA based on local seismicity and geological structure.

(a) Southern Sudan, Ruwenzori area, and Lake Edouard trough. Southern Sudan is dominated by relatively strong earthquakes with poor tectonic control (Girdler and McConnell, 1994). The Ruwenzori area experienced large earthquakes on 20 March 1966 ($M_w$ 6.8) and 5 February 1994 ($M_w$ 6.2) (National Earthquake Disaster Committee, 1994; Mavonga, 2007a).
(b) Virunga volcanic complex, Rutsuru basin and Masisi area. The Virunga volcanic complex is the largest of the Cenozoic volcanic complexes in the Kivu Province and the only one that is presently active. Earthquakes in the volcanic area generally have low magnitudes ($M_w < 4$).
(c) Lake Kivu basin, Ngweshe area and Ruzizi plain. As noted in the introduction to this paper, several large earthquakes have occurred in the region, such as $M_w$ 6.2 on 24 October 2002 and $M_w$ 6.0 on 3 February 2008.
(d) Lake Tanganyika Rift. Many larger magnitude earthquakes have occurred in the Tanganyika Rift. The best known are the events which occurred on 13 December 1910 at the southern end of Lake Tanganyika (M7.3), 22 September 1960 at the northern end of Lake Tanganyika ($M_s$6.5) (Zana and Hamaguchi, 1978), and 5 December 2005 ($M_s$6.8) in the central part of Lake Tanganyika.

### 5.4. Determination of seismicity parameters of seismic source zones

The seismic characteristics for each seismic source zone were modelled as a Poisson process following the standard engineering seismology assumptions. The parameters used to characterize each seismic source zone are:

(i) Mean seismic activity rate ($\lambda$).
(ii) Level of completeness of the earthquake catalogue ($M_{min}$).
(iii) Maximum possible earthquake magnitude ($M_{max}$).
(iv) The β-parameter derived from the Gutenberg–Richter (1954) "*b*-value", which indicates the relative number of large and small earthquakes, where $\beta = b \ln 10$.
(v) Focal depth. Detailed seismic studies indicate that the earthquake foci generally lie at depths of 10–20 km in the WRA (Zana, 1977; Zana and Hamaguchi, 1978; De Bremaecker, 1959; Wohlenberg, 1968).

The values of the parameters for each source zone are listed in Table 2.

**Table 2**
Seismicity parameters.

| Source zones | $M_{min}$ | $M_{max}$ | Beta ($\beta$) | Lambda ($\lambda$) |
|---|---|---|---|---|
| *Western Rift Valley* | 4 | 7.79 | 1.84 | 6.46 |
| (i) Ruwenzori–Lake Edouard trough | 4 | 7.29 | 1.84 | 2 |
| (ii) Virunga volcanic complex–Rutsuru–Masisi | 4 | 5.99 | 1.84 | 1.13 |
| (iii) Lake Kivu basin–Ngweshe–Ruzizi | 4 | 6.67 | 1.84 | 0.74 |
| (iv) Lake Tanganyika Rift | 4 | 7.79 | 1.84 | 3.17 |
| Upemba–Moero Rift | 4 | 6.99 | 2.07 | 1.95 |
| Congo basin | 4 | 6.09 | 2.39 | 1.81 |

$M_{min}$ – lower bound magnitude; $M_{max}$ – maximum expected upper bound magnitude; Beta ($\beta$) – *b*-value × ln(10), where *b*-value – slope of magnitude–frequency relation; Lambda ($\lambda$) – annual number of earthquakes above the lower magnitude bound.

### 5.5. Ground motion prediction equations

Ground motion prediction equations are important for estimating hazard. Generally equations derived for similar tectonic terrains elsewhere are used, as very few studies have been done in Africa. Attenuation relations for the Eastern and Southern Africa region based on the strong ground motion are virtually non-existent. Attempts were made by Jonathan (1996) and Twesigomwe (1997) to establish an average attenuation relation for the region. Jonathan's relation is based on random vibration theory using some earthquakes recorded by the digital stations in the region. Twesigomwe's relation 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). As for East Africa, because there is no strong motion database available for a regression analysis to estimate ground motion parameters as a function of magnitude and distance, it is necessary to resort to other, less direct, data sources. Tuluka (2007) derived an attenuation relationship by simulating strong motion of large earthquakes using recordings of small earthquakes (Frankel, 1995; Irikura, 1983, 1986). Earthquakes recorded at three stations on hard rock sites in the Kivu Province (Lwiro LWI, Kutale KTL, and Kunene KNN) were used in the analysis. The semi-empirically attenuation relationships determined for different source magnitudes are listed in Table 3.

### 5.6. Preparation of seismic hazard maps

Mavonga and Durrheim (2009) used the EZ-Frisk software (Risk Engineering, Inc., 2007) to prepare seismic hazard maps for 2%, 5% and 10% chance of exceedance in 50 years for various combinations of the seismic source zones, three attenuation equations, and two alternative focal depths. A 0.5° grid and 2%, 5% and 10% chance of exceedance in 50 years (which corresponds to return periods of 2475, 975 and 475 years, respectively) was used in the calculation. Three regional attenuation relationships for the strong ground motion were considered, two of these derived using data from the African continent: Mavonga (2007b) for the Western Rift Valley, and Jonathan (1996) for eastern and southern Africa. The relations derived by Atkinson and Boore (2006) for eastern North America, which have frequently been used to describe other stable continental regions (e.g. Kijko et al., 2002), were also considered. The output is a statistical estimate of the annual chance of exceedance as a function of the peak ground acceleration, PGA (Fig. 7).

**Table 3**
Ground motion attenuation in the Kivu Province (Tuluka, 2007).

| *M* (magnitude) | Attenuation relationship |
|---|---|
| 5 | $Y \approx R^{-1.1}$ |
| 5.5–6.5 | $Y \approx R^{-1.2}$ |
| 7 | $Y \approx R^{-1.3}$ |
| 7.5 | $Y \approx R^{-1.4}$ |

*Y* = peak ground acceleration, *R* = epicentral distance.

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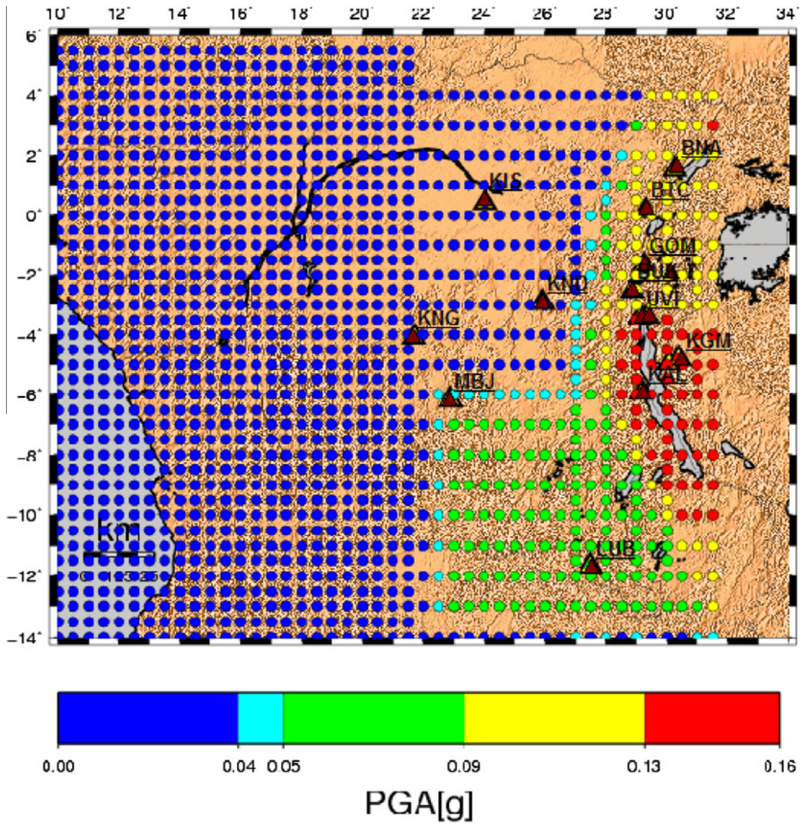


**Fig. 7.** Distribution of mean PGA values (in units of g) in the DR Congo and surrounding areas computed for 10% chance of exceedance in 50 years. The filled circles and triangles indicate the site PGA values and main cities, respectively.

The highest levels of seismic hazard were found to occur in the Lake Tanganyika Rift sub-zone, where PGAs in excess of 0.32 g, 0.22 g and 0.16 g are expected with 2%, 5% and 10% chance of exceedance in 50 years, respectively. The regions with the next high level of hazard are the other sub-zones in the Western Rift Valley, with the exception of the Virunga volcanic complex–Rutsuru–Masisi sub-zone where the seismic hazard (due mainly to the volcanic activity) is only moderate. The seismic hazard in the Congo basin diminishes with distance from the Western Rift Valley until, at a distance of about 450 km, the chance of exceeding a PGA of 0.05 g (the threshold value of engineering interest) is less than 10% in 50 years.

### *5.7. Seismic hazard zones*

From the probabilistic seismic hazard analysis in DR Congo and surrounding areas, four seismic hazard zones were identified based on investigation of seismicity and intensity of ground motion expected to occur:

- o Zone A (very high hazard), largely the Lake Tanganyika Rift zone where the PGA values of 0.32 g, 0.22 g and 0.16 g are expected to occur with probability 2%, 5%, and 10% in 50 years, respectively.
- o Zone B (high hazard), which includes the Lake Kivu basin, Ruwenzori and Lake Edouard region.
- o Zone C (moderate hazard), which includes Rutsuru, Masisi, Upemba and a part of the Congo basin close to Western Rift.
- o Zone D (low hazard), which includes the remainder of the Congo basin.

## 6. Conclusions

In recent decades, civil wars in the eastern provinces of the Democratic Republic of Congo have caused massive social disruptions, which have been exacerbated by volcanic and earthquake disasters. Seismic data were gathered and analysed as part of an effort to monitor the volcanoes and quantitatively assess the earthquake hazard. A local seismic velocity model was derived and used to relocate hypocenters of earthquakes associated with volcanic eruptions. Spatial and temporal trends were studied. Swarm-type seismicity, composed mainly of long-period earthquakes, preceded both eruptions the 2004 and 2006 eruptions of Nyamuragira. About a year prior to the eruptions a steady increase in seismicity at a constant rate was observed. It was attributed to the movement of magma in a deep conduit. In the last stage (1 or 2 months) before the eruption, the hypocenters of long-period earthquakes became shallower. These observations suggest that changes in the rate and location of long-period earthquakes, integrated with other available data (e.g. INSAR, GPS, geochemical, geological), may be used to characterize volcanic processes and forecast volcanic eruptions in the Virunga area.

Seismic hazard maps were prepared for the DRC using a 90-year catalogue compiled for homogeneous $M_w$ magnitudes. The highest levels of seismic hazard were found in the Lake Tanganyika Rift seismic zone, where peak ground accelerations (PGA) in excess of 0.32 g, 0.22 g and 0.16 g are expected to occur with 2%, 5% and 10% chance of exceedance in 50 years, respectively.

The outputs of this research can be used to monitor volcanoes and provide early warnings of eruptions and to assess the earthquake hazard. Authorities can use the findings to plan the settlement of displaced people, identify regions where buildings should be reinforced to improve their resistance to shaking, and to "build back better" following any future disaster.

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