Macroseismic survey of the 6 February 2016 KwaZulu-Natal, South Africa earthquake

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Abstract

On the 6th of February 2016 at 11:00 hours local time (0900 UTC), KwaZulu-Natal was struck by an earthquake of local magnitude M_L=3.8. The epicentre of the earthquake was located offshore in the Durban Basin. The earthquake shaking was widely felt within the province as well as in East London in the Eastern Cape province and was reported by various national media outlets. Minor structural damage was reported. A macroseismic survey using questionnaires was conducted by the Council for Geoscience (CGS) in collaboration with the University of KwaZulu-Natal (UKZN) which yielded 41 intensity data points. Additional intensity data points were obtained from the United States Geological Survey (USGS) *Did You Feel It?* programme. An attempt was made to define a local intensity attenuation model. Generally, the earthquake was more strongly felt in low-cost housing neighbourhoods than in more affluent suburbs.

Introduction

On the 6th of February 2016 at 11:00 local time (0900 UTC), KwaZulu-Natal province was struck by an earthquake of local magnitude M_L=3.8. Using the network of local South African National Seismograph Network (SANSN) and International Monitoring System (IMS) seismic stations, the earthquake was located offshore at 29.864°S and 31.329°E. The error ellipse of the location was found to be ±2.5 km and ±3.9 km in the major and minor axis, respectively. Since the hypocentral depth would have been unreliable at regional distances recorded with a sparse seismic network, the depth of the event was fixed at 6 km based on the work of Saunders (2017), who concluded that the majority of events in KwaZulu-Natal occur at this depth using synthetic waveform modelling. No aftershocks were identified after this event.

The routine practice at the Council for Geoscience is to fix depth at 5 km (e.g. Guzmán, 1978; Saunders et al., 2008) of tectonic earthquakes in South Africa. However, studies conducted by Brandt (2014), Mangongolo et al. (2017) and Kgaswane et al. (2018) indicate that brittle failure occurs at approximately 6 km. Thus, a more accurate hypocentral depth of 6 km was assumed during the location procedure.

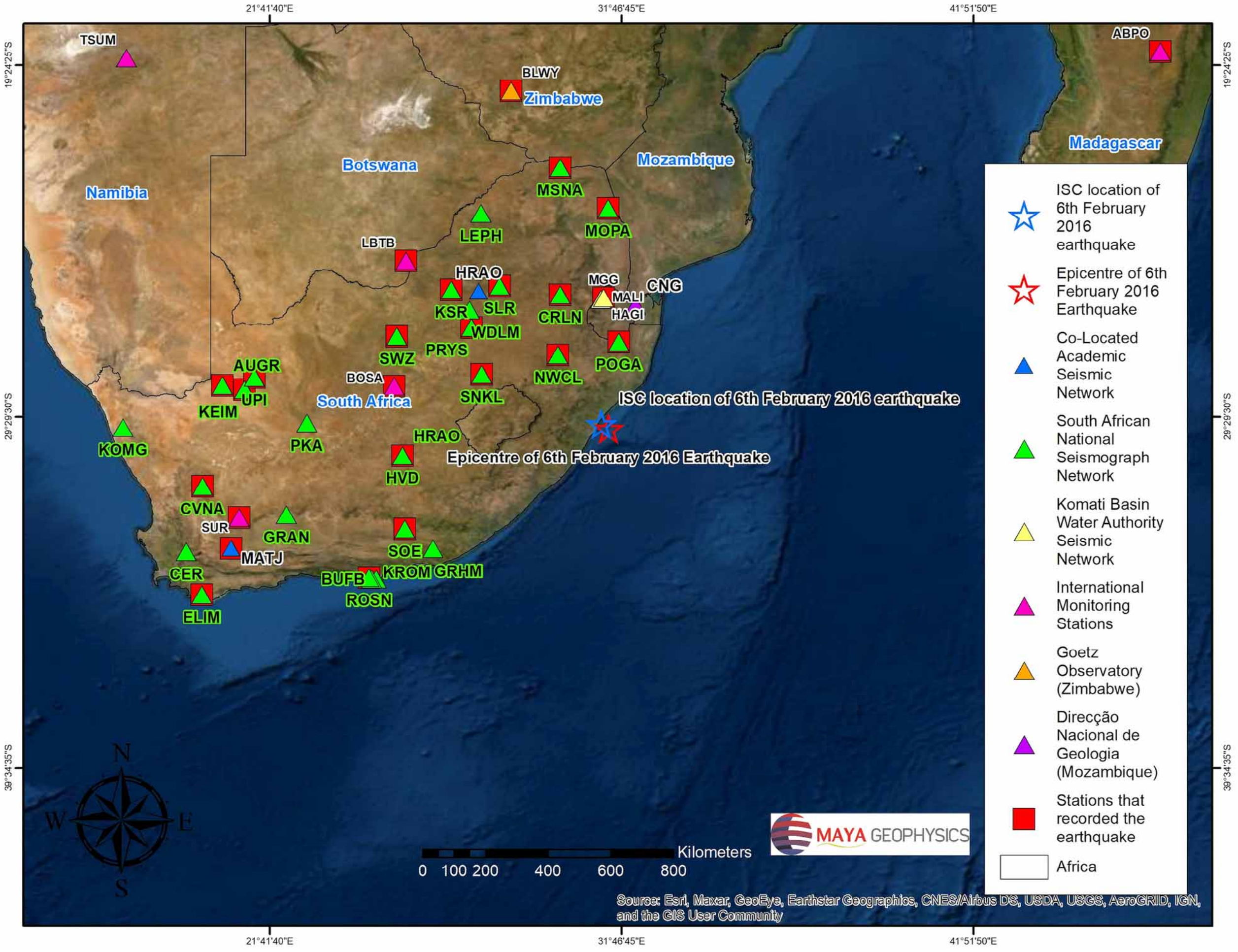
The USGS National Earthquake Information Centre (NEIC) also reported this event with body wave magnitude m_b=3.7 but with an onshore location at 29.552°S and 30.729°E using phase information from seven regional seismic stations. This prompted the need to re-analyse the earthquake location using local SANSN and regional phase information that had not been considered initially (Figure 1).

The event was re-analysed using the HYPOCENTER algorithm (Lienert and Havskov, 1995) which uses a damped least-squares procedure to iteratively solve the travel-time equation. The International Seismological Centre reviewed bulletin (ISC, 2021; Di Giacomo et al., 2014) location shown in Figure 1 also provided additional confirmation that the epicentre of this event was offshore and had incorrectly been located by NEIC.

The earthquake was felt widely in KwaZulu-Natal as well as East London in the Eastern Cape province and was reported by various national media outlets. A macroseismic survey was conducted by the Council for Geoscience in conjunction with the University of KwaZulu-Natal. People in low-cost housing felt the shaking more strongly than people in the more affluent areas, such as Umhlanga Rocks, which were much closer to the epicentre. Amanzimtoti, Hammarsdale and Umhlanga Rocks are located 50 km, 84 km and 30 km from the epicentre respectively. Minor structural damage was reported in low-cost houses at Hammarsdale while a long hairline crack in the floor tiles was also observed at the Hammarsdale Junction shopping centre (Figure 2a).

Seismic history of KwaZulu-Natal

KwaZulu-Natal is characterised by moderate levels of seismicity with several earthquake epicentres located along the KwaZulu-Natal northeast-southwest coastal faults (Figure 3). This suggests a relationship between epicentres and lineaments, although some events can be observed that cannot be correlated to any known lineaments. Focal mechanisms obtained by Saunders (2017) show normal faulting in southern KwaZulu-Natal,



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. The analysed (red star) and ISC (blue star) epicentre of the 6 February 2016 event and seismic stations.

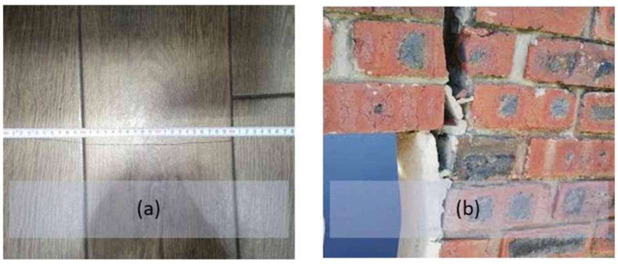


Figure 2. *Structural damage resulting from the 6 February 2016 KwaZulu-Natal offshore earthquake **(a)** Long hairline crack at the Vodacom store, Hammarsdale mall, **(b)** Damage to a government subsidised Reconstruction and Development Programme (RDP) home in Hammarsdale.*

whereas the 21 May 2009 $M_L=3.2$ event near Phuthaditjaba indicates reverse faulting.

The largest recorded earthquake in KwaZulu-Natal occurred on 31 December 1932 with a magnitude of $M_L=6.3$. It was felt in Port Shepstone, Kokstad and Johannesburg. The effects of this event were well documented by Krige and Venter (1933). This earthquake resulted in damage to several buildings constructed using inferior burnt bricks and clay. It originated from a fault running parallel to the coast (Krige and Venter, 1933). Several other events have been recorded in this area. Hartnady (1990) suggested that seismic activity in this area could either be a result of the propagation of the East African Rift System (EARS) southwards or epeirogenic origins involving the hypothetical sub-lithospheric Quathlamba seismicity hotspot presently located at ~30°S and ~29°E.

Instrumental seismicity of the province may be correlated to pre-existing zones of weakness. Several faults that originated from the Gondwana breakup approximately 180 million years ago, lie along the coast with a northwest-southeast trend (Maud, 1961; Von Veh, 1994). The north of the province is typified by northwest-southeast faults perpendicular to the coast and characterised by a series of horsts and grabens (Watkeys and Sokoutis, 1998). A prominent active fault in the province is the east-west oriented Tugela fault (Figure 3). Several thermal springs and carbon dioxide exhalation sites are located along this fault indicating neotectonic activity (Hartnady, 1985; Johnson et al., 2017).

Singh (2016) stated that the significant number of historical events that were reported along the coast may be attributed to historical population patterns where more communities settled in these areas in comparison to those that settled inland. Presently, there are very few seismic monitoring stations in the province, and they are sparsely distributed, as seen in Figure 1. According to Saunders (2017), the minimum magnitude detection threshold for SANSN in KwaZulu-Natal is $M_L=3$. This has resulted in the inability to detect critical micro-earthquakes

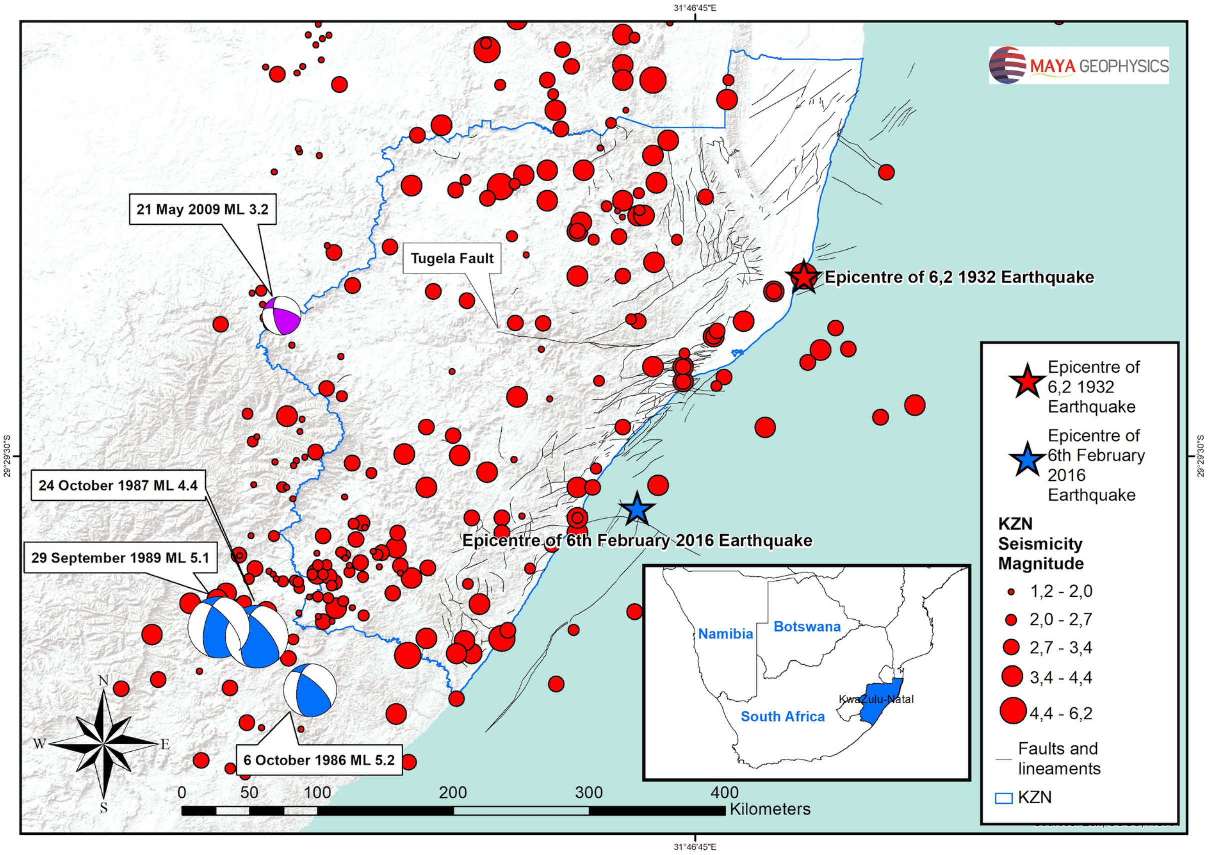


Figure 3. *Seismicity of KwaZulu-Natal superimposed on fault lineaments in the province. Focal mechanisms of selected events represented by blue and purple beach balls denoting normal and reverse faulting, respectively.*

whose epicentres are located on active structures, and in poorly constrained source parameters for events that are detected.

Intensity scales

The assessment of earthquake intensities provides a qualitative method of estimating earthquake ground motion at a given location in terms of its observed effects (Musson and Cecić, 2002; Prakash et al., 2011). The level of intensity at a location depends on the strength of the earthquake, epicentral distance and local geologic conditions. Earthquake intensities have a wide range of applications. These include the calibration of source parameters of historical earthquakes that were not instrumentally recorded, identifying regions where ground motion is amplified, extrapolation of strong ground motion, seismic hazard and risk assessment (Zsíros, 1997; Musson, 2000; Musson and Cecić, 2002; Atkinson, 2007; Prakash et al., 2011).

Giles (2013) defined an intensity scale as a measure that uses descriptive evidence to categorise the severity and the impact of an earthquake on the local environment and buildings. Intensity scales have evolved and several scales are currently in use. Musson et al. (2010) estimated that the number of intensity scales that have been used historically may reach three figures although about eight have been more widely adopted. In this study, we chose to focus on the Modified Mercalli Scale of 1956 (MM56) published by Richter (1958), which has widely been used in South Africa and has most recently been applied in macroseismic studies of moderately-sized events by Midzi et al. (2015a) and Midzi et al. (2015b).

Macroseismic survey and data analysis

Following the occurrence of the earthquake, a collaborative effort ensued between the Council for Geoscience and the University of KwaZulu-Natal. Field teams were dispatched to Durban and Hammarsdale in KwaZulu-Natal to investigate the effects of the earthquake in the province. The primary source of information for the survey was questionnaires, which were distributed by field teams canvassing shopping centres, homes, and office buildings.

The questionnaire was provided by the Council for Geoscience and has been used for similar macroseismic survey studies such as the M_L=5.5 2014 Orkney earthquake (Midzi et al., 2015a). Ninety-two questionnaires were completed through the efforts of the field teams. Additionally, four questionnaires were completed through telephonic interviews leading to a total of ninety-six. Social media and newspaper reports were not utilised due to the difficulty of reliably estimating the location of the observers. The questionnaires comprised 24 multiple choice questions, each addressing a specific aspect of the earthquake effects. The questionnaires also asked for the address of the participant, which was used to determine the spatial location of the participant at the time of the earthquake using Google Maps. In cases where no address had been provided, participants were contacted either by email or telephonically to obtain their addresses. The initial analysis of the data from the survey was carried out by Zulu (2016).

Due to limited financial and human resources, the data collected from field surveys were limited and collected only from suburbs of Durban and Hammarsdale. To augment this dataset, a decision was made to include online information obtained from the United States Geological Survey's (USGS) "*Did You Feel It?*" programme (Wald et al., 2012). The USGS collected 24 observations from seven suburbs. It should be noted that the USGS does not disclose individual responses but provides an aggregated intensity summary information for each location (Table 1).

Observations and intensity data points (IDPs)

The procedure of Musson and Cecić (2002) was followed in rendering the observations from the questionnaires into intensity data points. The procedure requires that the seismologist gathers available information and therefore it follows that there is increased confidence in areas with more observations and vice versa. The initial step was to systematically catalogue the observed data from questionnaires according to the suburb or district it was captured from. The number of observations captured from each suburb or district during the local survey is represented in blue in Figure 4 while USGS observations are indicated in red.

For the questionnaires obtained during the fieldwork, locations of the suburbs and districts were obtained from the National Geospatial-Intelligence Agency online database tool (http://geonames.nga.mil/namesgaz). We reviewed the observations recorded in each questionnaire and estimated the measure of intensity that best suits the summary description based on the MM56 scale. Nineteen intensity data points were created based on single observations while four were created using at least five observations.

Since the USGS does not disclose individual responses, we adopted a three-pronged approach for reconciling the two datasets. In areas where data was only available from one source, then that available source was used. In areas where both sources recorded an equal level of intensity, that assigned intensity adopted. In areas where both sources had data, but the assigned intensities were different, the higher intensity was used so that the largest possible acceleration is accounted for when applied to ground motion prediction.

The intensity data points obtained from the USGS were obtained from areas where the local field team did not manage to travel to except for Durban and Ballito. The intensity of III assigned to Durban for the USGS data was similar to what was obtained from the local surveys and therefore it was taken as it is. For Ballito, the USGS assigned an intensity of II while level V was assigned from the local survey as the entire building shook and crockery was damaged. The local survey was given precedence as there was structural damage even though limited observations had been collected because in seismic hazard analysis we must account for the largest possible earthquake acceleration that can occur in an area to mitigate damage (Kijko, 2011).

The greatest number of intensity data points had an intensity level of III. Levels III-IV and IV had one and two intensity data points respectively. The number of intensity data points obtained

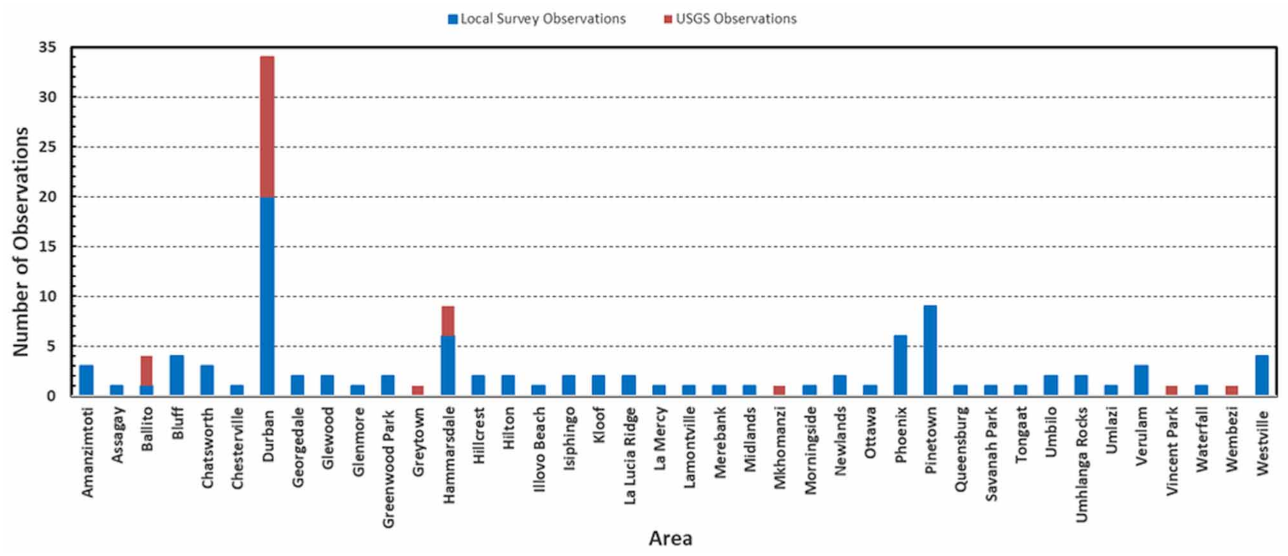


Figure 4. *The number of observations used to create each data point divided into areas.*

for each intensity level is shown in Figure 5 while their spatial distribution is shown in Figure 6. The highest level of intensity (V) was observed at Ballito and Hammarsdale which are located at epicentral distances of approximately 34 km and 79 km, respectively. The level of intensity that is felt during an earthquake depends on the magnitude, location, and epicentral depth and overlying soil conditions.

The distribution of intensity with epicentral distance was plotted (Figure 7) to gain an understanding of the attenuation of seismic waves in the region. An attempt was made to define a local intensity attenuation relation, which we compared to the model of Bakun and Scotti (2006) for the French stable continental region as South Africa has also been described as a stable continental region (Johnston et al., 1994)

Using the Peruzza (1996) relation in equation 1 for intensity and epicentral distance, an optimal fit for the data was obtained.

$$I_0 - I = -a_1 - a_2 In\, R - a_3 R \qquad (1)$$

where $a_1 \ldots a_3$ are coefficients, R is the hypocentral distance in km, I is intensity and I_0 is the maximum intensity at the epicentre.

Table 1. Responses obtained from the USGS *"Did You Feel It"* programme.

Area	Province	Assigned MM56 Intensity	Responses
Hammarsdale	KwaZulu-Natal	III	3
Durban	KwaZulu-Natal	III	14
Ballito	KwaZulu-Natal	II	3
Greytown	KwaZulu-Natal	IV	1
Mkhomanzi	KwaZulu-Natal	III	1
Wembezi	KwaZulu-Natal	III	1
East London	Eastern Cape	II	1

The empirical relation between magnitude, M, and intensity at the epicentre, I_0, (Richter, 1958) is given below:

$$I_0 = \frac{3}{2}M - 1 \qquad (2)$$

By substituting for I_0, (2) in (1), a relation between intensity, I, local magnitude, M, and hypocentral distance, R, can be obtained.

Our model is given by:

$$I = 0.93 + 1.27M - 1.73\, log_{10}(R) \qquad (3)$$

The newly developed relationship appears to display a bias in attempting to fit low and high-intensity values which may be a result of local site effects. The intensity data points labelled (a) in Figure 7, would have been expected to exhibit higher intensities as they are located considerably closer to the epicentre at 30 to 60 km. Upon closer inspection, most of these intensity data points are in affluent suburbs such as La Lucia, Hillcrest and Glenwood, with well-built housing. It is therefore sensible that the effects of the earthquake would have been felt to a lesser extent than in (b) which is in Hammarsdale. Some of the observations in Hammarsdale which resulted in structural damage (see (b) of Figure 2) are from poorly built houses and therefore it is unsurprising that this resulted in structural damage even though they were located further from the epicentre.

Isoseismal map

Geostatistical methods, which include the natural neighbour and Kriging techniques, have been used in attempts to produce objective isoseismal maps (Sirovich et al., 2002; Schenková et al., 2007). According to Tily and Brace (2006), the natural neighbour technique is most suitable for the interpolation of irregularly distributed data, which are dense in some areas and sparse in others. As can be observed in Figure 6, the intensity data points in this study are tightly clustered in the near-field of the epicentre and scattered in the far-field, therefore this dataset was deemed to be suitable for interpolation using the natural neighbour technique.

The resulting isoseismal map is shown in Figure 8 below. The warmer colours represent higher levels of intensity as indicated in the map legend. The greatest levels of intensity (IV and V) can be observed towards the north in Hammarsdale, Assagay, Ballito and Greytown. Coastal areas that are much closer to the epicentre such as Umhlanga Rocks, Durban, and Bluff, interestingly were amongst some of the areas where moderate levels of intensity III were recorded. The lowest intensity levels (I to II) were observed in Hilton, Midlands and Hillcrest.

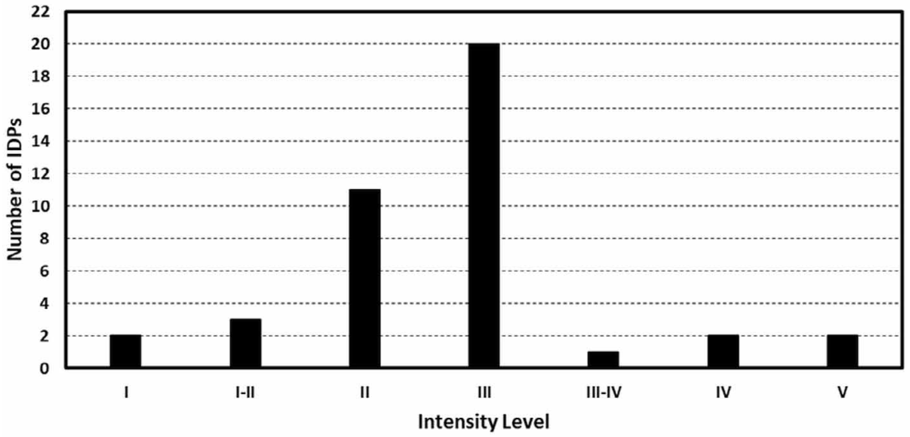


Figure 5. *The number of intensity data points obtained for each intensity level.*

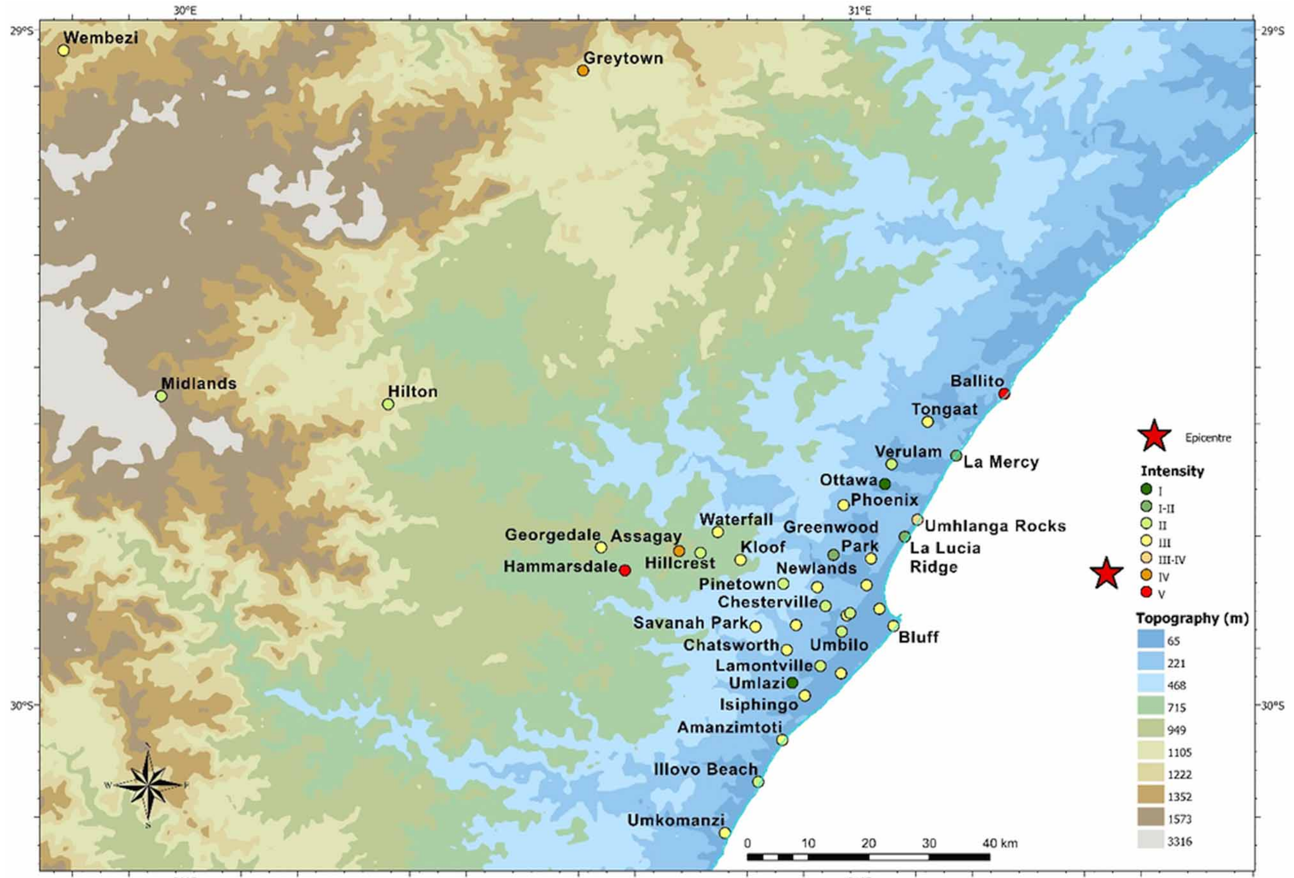


Figure 6. *Spatial distribution of intensity data points superimposed on the topography of KwaZulu-Natal.*

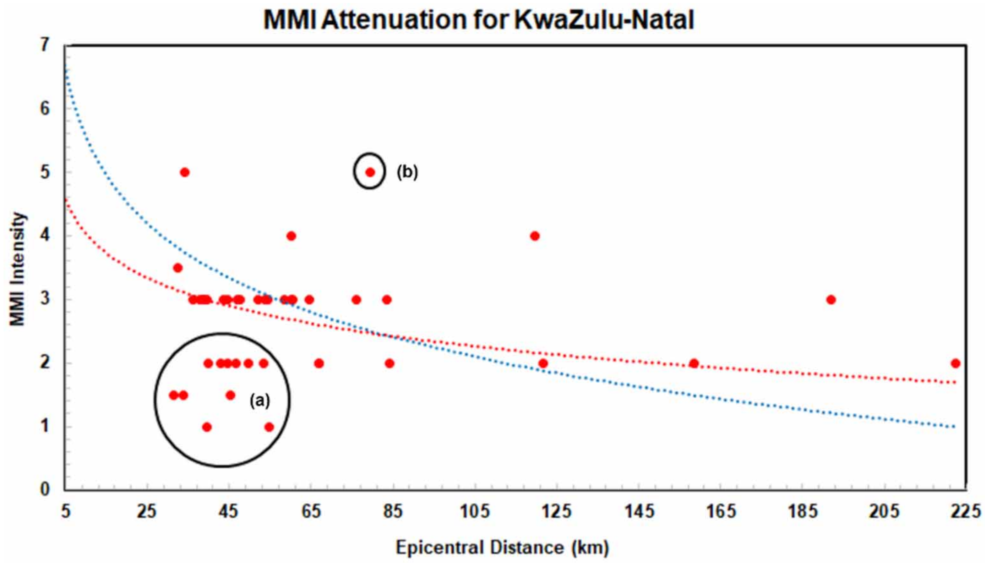


Figure 7. *The intensity-distance plot for the intensity data points obtained for the 6 February 2016 KwaZulu-Natal earthquake. The blue dashed line represents the modified Bakun and Scotti (2006) and the red dashed line represents the new intensity-distance attenuation model. Anomalous data points (**a**) and (**b**) are discussed below.*

Discussion and conclusion.

It is interesting to note that areas located at a distance less than 40 km from the epicentre such as La Lucia, La Mercy, and Newlands experienced intensity levels less than II. These are relatively affluent suburbs with well-built houses whereas Hammarsdale, which is located 80 km away, experienced damage to low-cost houses that did not have plaster finish. This may serve as an illustration of the critical importance of strict adherence and enforcement of the national building codes on seismic loading in South Africa (SABS, 2011).

The epicentre of the 6 February 2016 earthquake was in the Durban Basin. This is an offshore extensional rift basin formed during the Gondwana breakup. The south of the basin is bounded by a major transform fault which marks the beginning of the Agulhas-Falklands Fracture Zone (Hicks and Green, 2016; Carsandas et al., 2017). Using the NEIC earthquake catalogue extending from 1900 to 2017, Hicks (2017) states that the offshore Durban basin is seismically stable. The occurrence of the 6 February 2016 event is in stark contrast to this view and serves as evidence that there is still notable seismic activity along the coast. These events may be emanating from offshore neotectonic activity (in the Quaternary) as previously reported by Ben-Avraham (1995) and Reznikova et al. (2005) based on marine geophysical data.

The largest earthquake recorded in KwaZulu-Natal province, which occurred in 1932, also originated from an offshore source. The current configuration of seismic monitoring stations in South Africa does not permit the accurate detection and location of offshore events with a magnitude less than M_L=3. This prevents the development of a comprehensive understanding of physical processes that may be occurring in offshore sources, which is a key input in seismic hazard studies for the country. We, therefore, suggest that authorities and academic institutions prioritise the study of offshore sources as this could help mitigate the effects of damaging earthquakes. The deployment of offshore underwater seismic monitoring stations would also be a welcome development as this would assist in constraining the location of earthquakes along the coast.

The isoseismals from the earthquake are irregular rather than following elliptical or circular patterns as is often seen in isoseismal maps. This is possibly a consequence of the distortion in distribution and incompleteness of the data which was mainly collected from metropolitan Durban and a few other areas in the province. It is interesting to observe that the isoseismal maps of the 31 December 1932 and 5 October 1986 events are also irregular (Krige and Venter, 1933; Graham and Fernández, 1987). These authors attributed irregular isoseismals to anomalous amplification because of local geology. Along the Umfolosi river, the damage was more severe due to moist alluvium soils amplifying the seismic energy.

Meunier et al. (2008), using earthquakes from California, Taiwan and Papua New Guinea suggested that steep areas are prone to topographic site effects. This could be the underlying cause of the high intensities that were experienced in some areas such as Greytown (1173 m), Assagay (827 m) and Hammarsdale (654 m) to the west in comparison to areas the east as seen in Figure 6. Assagay and Hillcrest are close to each other but there is a discrepancy in observed intensities between them. This scenario could have benefitted from the availability of more macroseismic observations in these areas to arrive at a more probable conclusion as there was a total of three observations altogether in these areas.

Local geology is known to be an influential factor in earthquake ground motion. In sedimentary basins, this leads to amplified levels of earthquake shaking due to the acoustic impedance that results from seismic waves being trapped between the bedrock and sediments (Zaharia et al., 2008). Midzi et al. (2015b) attributed the higher-than-expected intensity observed for the M_L=5.5 Orkney, South Africa earthquake in Durban (approximately 570 km from epicentre) to be a consequence of the amplification of thick sedimentary cover along the coast where there are young unconsolidated Cenozoic sediments. This is an important consideration in seismic hazard studies and the Council for Geoscience is presently conducting a microzonation study of KwaZulu-Natal which will be useful in estimating the response of soil layers when an earthquake occurs and thus the variation of ground motion characteristic on the ground surface. These outcomes can then be accounted for when designing new structures or retrofitting existing ones.

The rocks of the province are of Archaean to Cenozoic age. A segment of the southern margin of the Archaean Kaapvaal craton extends into northern KwaZulu-Natal (Figure 9). Together with the complex Namaqua-Natal Metamorphic province, they are the foundational geological units of the province. This margin of the Kaapvaal craton is a granite-greenstone terrain (De Beer and Meyer, 1984). On the south-eastern flank of the Kaapvaal craton in KwaZulu-Natal lies the Meso-Archaean Pongola Supergroup which is made up of the lower volcanic Nsuze and sedimentary Mozaan Groups (Wilson et al., 2013).

The mainly basement rocks of the ~1.1 Ga Namaqua-Natal Metamorphic Province and the Palaeozoic Natal Group sandstone outcrop from the southern edge of the Kaapvaal craton towards the south coast (Eglington et al., 1989; Thomas, 1989; Marshall and von Brunn, 1999). Karoo Supergroup sedimentary rocks that range from Palaeozoic to Mesozoic age are found in the central part of the province extending towards the Drakensberg in the west. The east coast consists of the much younger Cenozoic Zululand Group sandstone and mainly unconsolidated sediments.

Correlating the geology to the intensity data points appears to be a complex process considering the paucity of data in this study. We observed that some intensity data points with high intensities such as Hammarsdale and Assagay are located within the Natal Group. The geology of the area close to Hammarsdale mall is underlain by a mantle of mainly transported colluvium and residual soils overlying a weathered sandstone bedrock (Maphumulo, 2019).

Seismic waves travel faster through the bedrock whereas the less consolidated colluvium would be prone to slowing down the seismic waves. This increases the amplitude and duration of ground shaking as the energy is entrapped, leading to more severe ground shaking than would be expected at a site (Liam-Finn and Wightman, 2003). Therefore, the anomalous intensity observed in these areas may be attributed to a

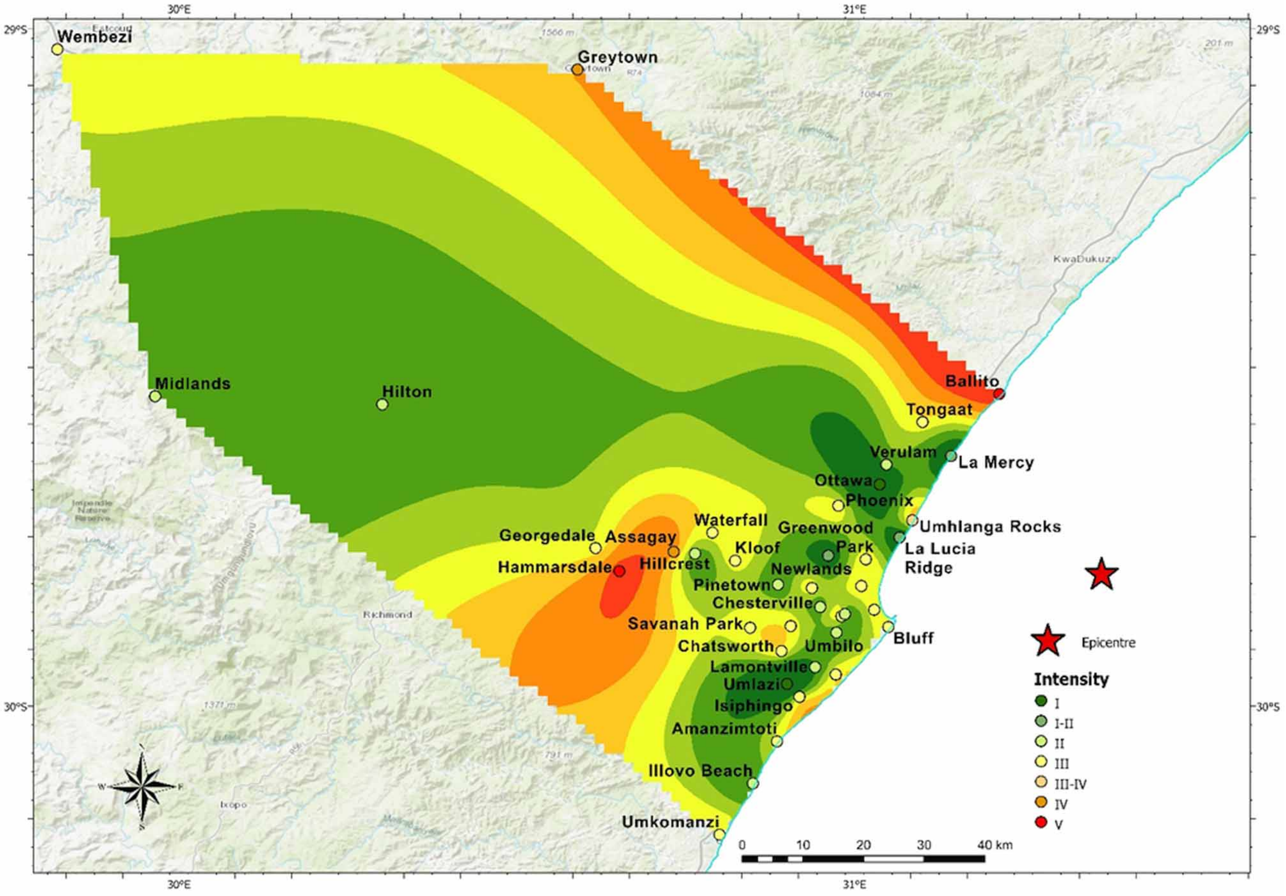


Figure 8. *Isoseismal map of the 6 February 2016, KwaZulu-Natal earthquake.*

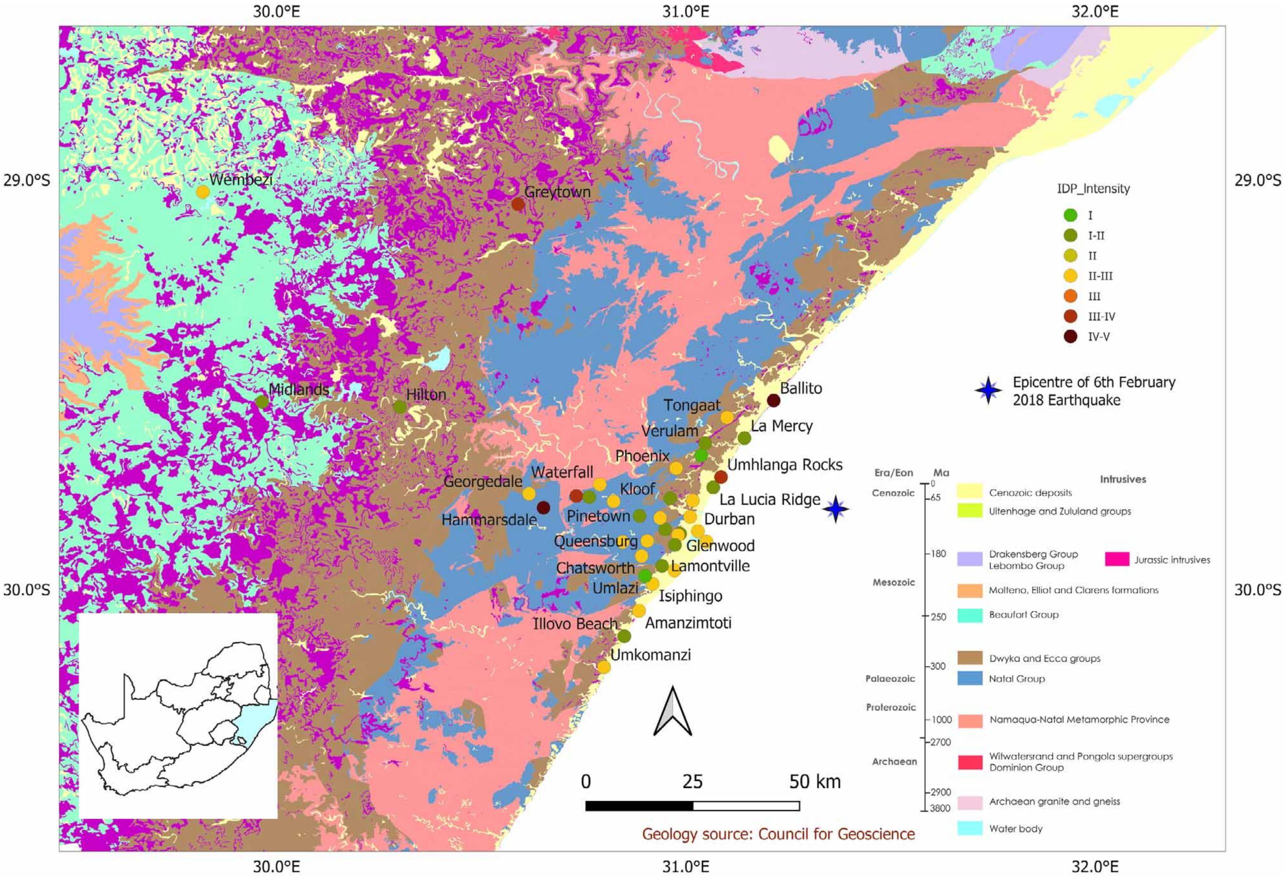


Figure 9. *Generalised geological units of the KwaZulu-Natal region at a scale of 1:250 000, intensity data points of 6 February 2016 event plotted in the background (data from Council for Geoscience).*

combination of low-cost housing as well as amplification resulting from the acoustic impedance contrast of the colluvium and sandstone bedrock associated with shear wave velocity disparity. Similarly, the anomalous Ballito intensity data point may also be a result of amplification effects as it is located within the Cenozoic Maputaland Group, which consists of unconsolidated estuarine muds and shelly sands.

This study has attempted to emphasise the need to develop a better understanding of the seismicity of KwaZulu-Natal and that what was historically considered to be an area with low levels of seismicity is characterised by moderate seismicity. Off-shore seismic sources pose a risk to South Africa and there is a need to extend the current seismic monitoring network to permit the detection of small off-shore seismic activity to develop our understanding of the seismic potential posed by offshore active structures. There is also a clear correlation between the quality of buildings and the amount of earthquake damage that they experience in the province. This serves to remind civil authorities of the need to enforce the national building codes relating to seismic loading.

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