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ORIGINAL ARTICLE

Macroseismic survey of the ML5.5, 2014 Orkney earthquake

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Abstract On 5 August 2014 at 1222 hours (local time), an earthquake of local magnitude ML=5.5 occurred in the Orkney area in the North West Province, South Africa. The earthquake shaking was felt widely in South Africa as far as Cape Town as well as in Maputo, Mozambique, and Gaborone in Botswana. One person was killed when a wall collapsed on him, and more than 600 houses were damaged. Following the earthquake, many people submitted reports to the Council for Geoscience (CGS) through an online questionnaire which recorded their experience, whilst others reported the event and its effects on social networks like Twitter and in newspapers. The CGS also sent out a team of scientists to further assess the effects of the event in the community by interviewing members of the public and completing additional questionnaires. A total of 866 observations were collected. Analysis of the collected macroseismic data produced 170 intensity data points which showed that a maximum intensity of VII was experienced in communities located in the epicentral area. The observed attenuation of intensity values was comparable to that observed on the French stable continental region especially in the area of 600-km radius from the epicentre. Airborne geophysical data were used to try and identify the fault along which the earthquake occurred. This was necessary as there was no surface expression of the earthquake and no previously identified fault near the epicentre. The interpretation of the data showed a fault located about 500 m from the epicentre appearing to form a boundary to the east of located aftershocks.

Keywords South Africa · Earthquakes · Intensity · MMI scale · Questionnaires · Macroseismic field · Epicentre

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1 Introduction

At around midday (1222 hours local time) on 5 August 2014, an earthquake of local magnitude, ML5.5, occurred in the Orkney area in the North West Province, South Africa (Fig. 1a). Using the national network as well as the cluster networks of stations located in and around the Klerksdorp–Carletonville–Johannesburg area (Fig. 2), the Council for Geoscience (CGS) recorded the event and reported its epicentre at the coordinates 26.942° S and 26.818° E. The error ellipse of the location has a major axis of 1.2 km and a minor axis of 0.6 km.

The event was estimated to have occurred at a depth of 4.7 km (Fig. 1b), with an error of 1.2 km. More than 400 aftershocks were recorded during the first day

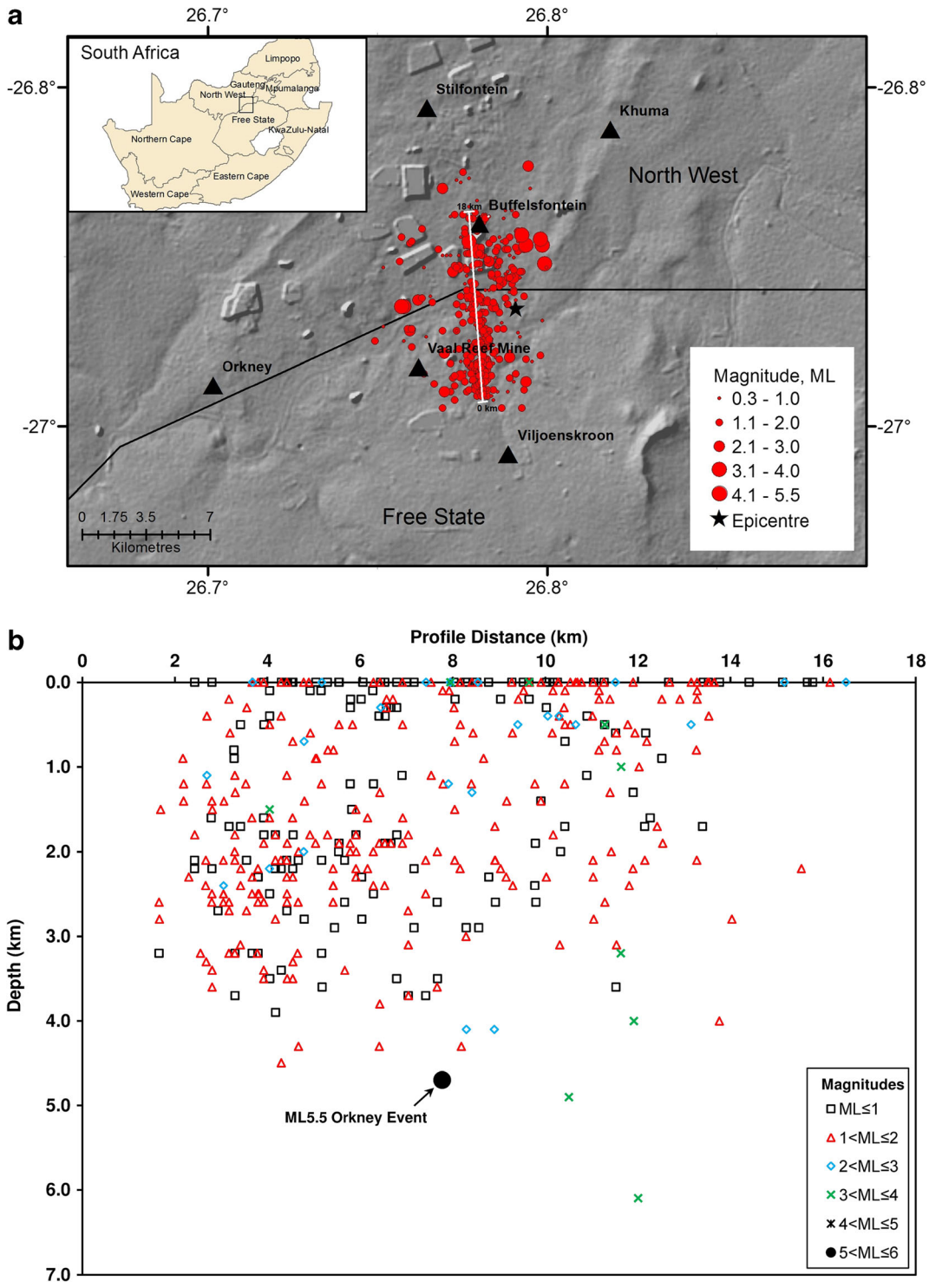

Fig. 1 **a** The locations of the main 5 August 2014 Orkney earthquake (*black star*) and related aftershocks (*red points*). The *white line* represents the location of an 18-km-long depth profile, shown in Fig. 1b .**b** Depth profile of aftershocks related to the 5 August 2014 Orkney earthquake (shown in Fig. 1a)

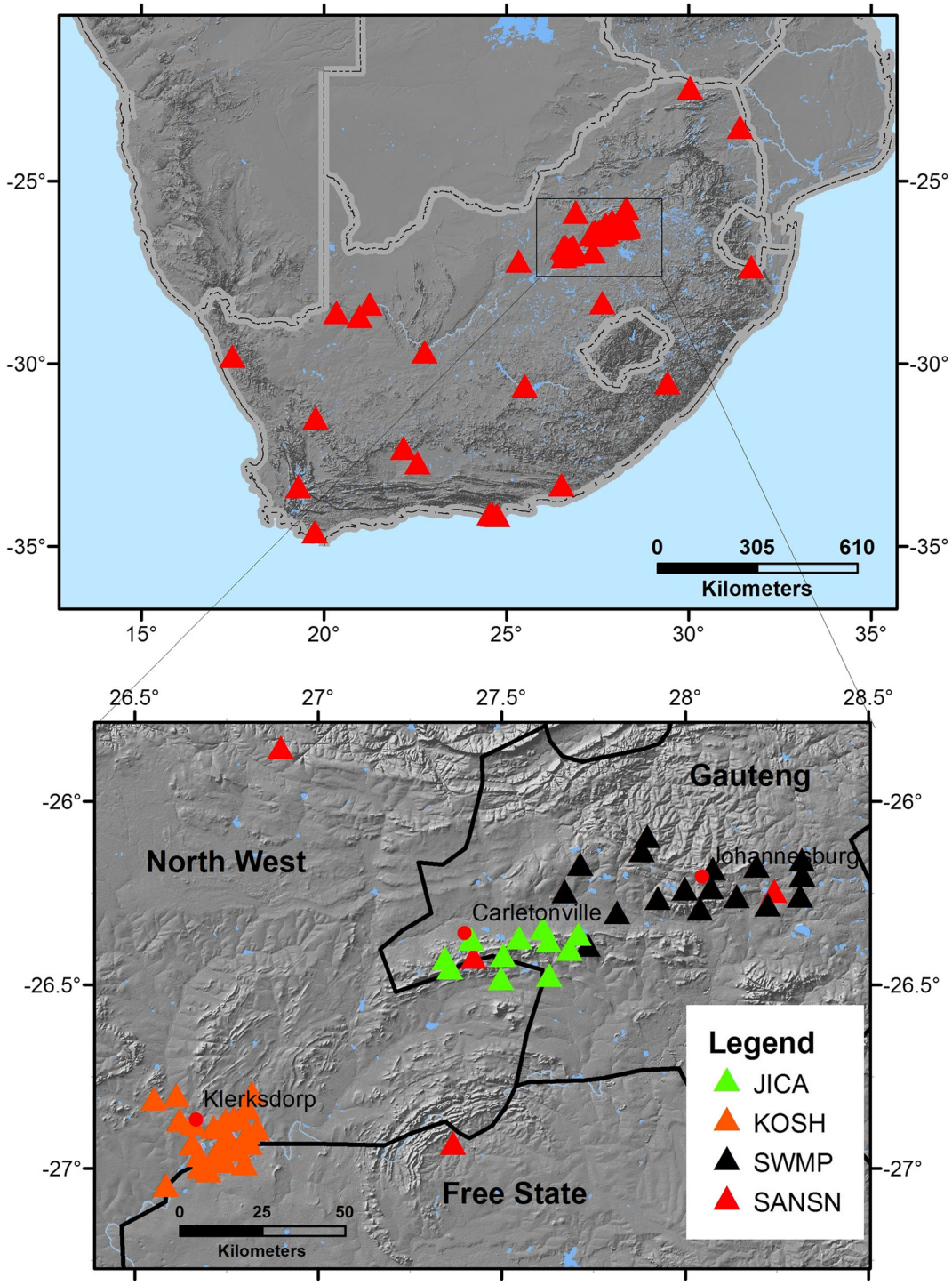

Fig. 2 The South African National Seismic Network (SANSN) and cluster networks (KOSH, JICA and SWMP) of seismic stations that recorded the 5 August 2014 Orkney earthquake

following the main event, and they continued for several days after. Most of the aftershocks were located at a depth shallower than the main event, with two clusters observed at about 2 km in the southern part of the profile and at 0.5 km towards the north. The largest recorded aftershock had a magnitude of ML3.9 and occurred on the same day, 5 August 2014 (1346 hours local time). The event resulted in shaking on the surface which was felt in the Orkney area, causing further panic. Further investigation of the aftershock sequence is necessary as there is a strong possibility that some of the events so far included as aftershocks could actually be part of the background seismicity of the area given that the area is quite active. Since the KOSH network was installed, an average of about 150 earthquakes is located in the area per month. The largest event prior to this ML5.5 event was the ML5.3 Klerksdorp event which occurred on 9 March 2005 and resulted in severe damage in mines as well as to structures on the surface.

The shaking from the main earthquake was widely felt, with reports from as far afield as Johannesburg, Pretoria, Durban, Cape Town, Gaborone in Botswana and even as far as Maputo in Mozambique. Some damage was observed on houses in the Orkney, Stilfontein and Khuma areas (Fig. 3), which are located at epicentral distances of 15.8, 11.8 and 11.0 km, respectively. Most of the damage to houses was observed in Khuma. Many people were injured, and one person was reported to have died as a result of a wall collapsing on him. According to news reports (News24 and BBCNews, 5 August 2014), AngloGold Ashanti, a mining company, reported that 17 employees at two mines in the Orkney region sustained minor injuries.

A preliminary geophysical investigation of the area was conducted by interpreting high-resolution airborne magnetic data to detect any possible structural control on the main event and aftershocks. The result, shown in Fig. 4, points to the existence of two geological

Fig. 3 Examples of observed damage to houses in the Orkney (**a**), Stilfontein (**b**, **c**) and Khuma (**d**) areas, which are located at epicentral distances of 15.8, 11.8 and 11.0 km, respectively. The photos of damage were taken by the CGS survey team during intensity damage survey

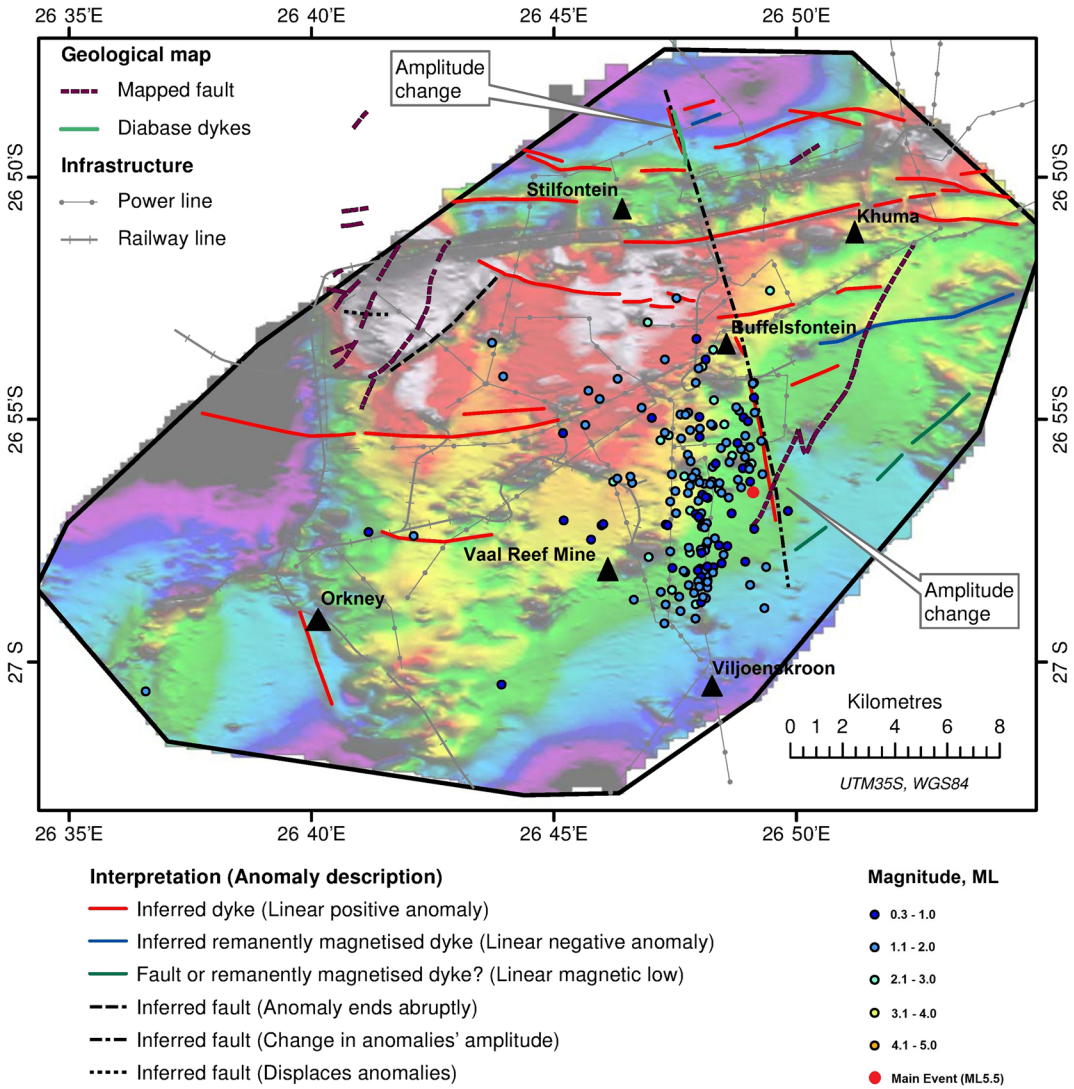

Fig. 4 Magnetic interpretation, mapped faults (from the 1:250,000-scale geological map) and aftershocks overlain on the magnetic data

structures, each located east of the aftershock sequence that can be the sources of the main event and aftershocks. Follow-up ground geophysics studies are necessary to obtain more conclusive information to assist in identifying these as possible seismogenic faults where the events occurred.

2 Macroseismic survey and data analysis

Macroseismic intensity data play an important role in the seismological, engineering and loss modelling communities (Midzi et al. 2013). They provide the much needed and often previously unavailable information for constraining the location and magnitude determination of historical events and for the reconstruction of shaking distributions. The data can also be useful in the selection of appropriate ground-motion prediction equations which are calculated either by comparing intensity values with those of other regions of similar tectonics (e.g. Bakun and McGarr 2002; Allen and Wald 2009) or by direct comparisons of intensity values with ground-motion predictions of peak ground acceleration and response spectral ordinates (e.g. Scherbaum et al. 2009; Delavaud et al. 2009). In South Africa, Midzi et al. (2013) compiled an intensity database containing 57 earthquakes, using

the Modified Mercalli Intensity scale, MMI-56 (Richter 1958).

Following the earthquake of 5 August 2014, the CGS conducted a macroseismic survey to investigate the effects of the event in the region. The macroseismic observations were compiled from a variety of sources, primarily using questionnaires, supplemented by newspaper reports and social media reports such as those from Twitter. However, in most cases, social media reports do not have a detailed description of the experience of the observer as well as their exact location; thus, this information was mainly used as an additional source of information. A few intensity data points (IDPs) were created using the Twitter information where it was the only source available. The questionnaire used has 19, mostly multiple choice, questions, each of which addresses a specific aspect of earthquake effects.

2.1 Observations and intensity data points

The observations were obtained from the following sources:

(a) Online questionnaires submitted by individuals who had felt the shaking;
(b) Questionnaires filled during interviews conducted by CGS scientists at homes, shopping malls, workplaces and schools, in the North West, Free State, Gauteng and Mpumalanga provinces of South Africa; and
(c) Twitter messages and newspaper reports.

A total of 866 observations were collected from the abovementioned sources, and their spatial distribution is shown in Fig. 5. As expected, the questionnaires obtained during interviews produced the most number of observations.

The methodology followed to translate the observer information into IDPs is essentially that recommended by Musson and Cecić (2002) and implemented by Midzi et al. (2013). The first step in the analysis of the observations was to sort them according to places, where the places were defined as suburbs or districts in the region. The locations of the places were obtained using gazetteers of places such as the online GeoNames database (http://geonames.nga.mil/ggmagaz/) and Google Earth.

All the individual intensity indicators per question in the questionnaires for each place were then summarised. Intensity values were assigned to the sorted and grouped

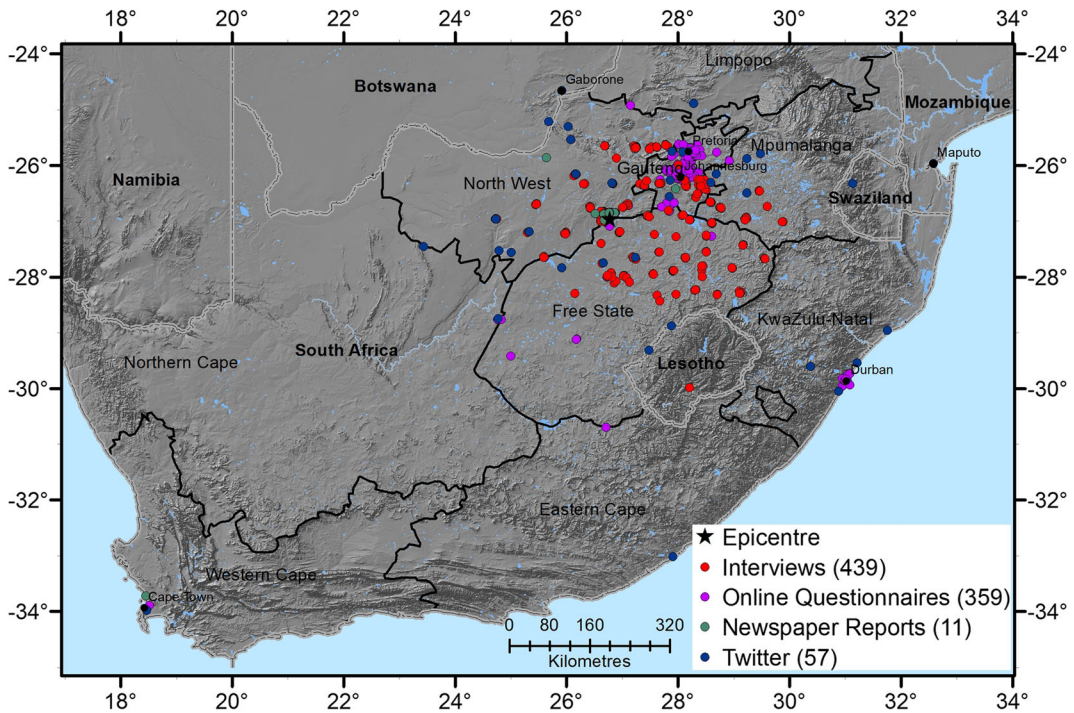

Fig. 5 Spatial distribution of observations analysed for the 5 August 2014 Orkney earthquake. In *brackets* are the numbers of observations obtained of that type. The *black star* indicates the location of the earthquake

observations by comparing the summary of the observations for each place with the descriptions given for the intensity degrees on the MMI-56 scale. This was done by identifying which of the descriptions for the various intensity degrees best fits the sum of the data collected for the particular place under consideration. As stated by Musson and Cecić (2002), it is important in this process not to lose focus in pursuit of details of individual diagnostics. The correct assignment is the one that best expresses the generality of the observations. Following the process described above, a total of 170 IDPs were created (Fig. 6).

On analysing the created IDPs, it was observed that many (44) were created using only one observation, thus reducing confidence in those results. However, 70 IDPs were created using at least five observations. The most reliable are the five created using more than 20 observations (i.e. Brummeria, Centurion, Randburg, Sandton and Western Bypass, all indicated in Fig. 7).

The numerical distribution of intensity levels obtained is shown in Fig. 8, which shows that many of the IDPs, 89, had an intensity value of IV. The highest intensity value obtained was VII, which was experienced at six places, namely Khuma, Orkney, Stilfontein, Klerksdorp, Vaal Reef Mine and Buffelsfontein (for the places, see Fig. 1a). All of these places are located within 20 km of the epicentre.

In order to obtain a better understanding of the distribution of the obtained IDPs, an intensity–distance curve was plotted (Fig. 9). This plot serves to illustrate the importance of the collected data and to clarify the attenuation of intensity levels and, hence, the attenuation of seismic waves in the region. In the near field (distance less than 20 km), the intensities do not show any evident trend but are constant at intensity level VII. This could be due to saturation of the ground-motion amplitudes in the near field. However, beyond the near field, the intensity values decrease gradually down to intensity II at about 600 km, though strong scatter is observed in the values. The main source in scatter could be the variation in site effects due to local geological conditions. Intensity values of IDPs located at around 600 km and beyond are higher than expected for their epicentral distances. This is clear for IDPs (a) to (d), marked in Fig. 9, which are for sites in Umhlanga and Umlazi (epicentral distance of 566 km, (a) in Fig. 9), Durban (569 km, (b)), Maputo (649 km, (c)) and Cape Town (1213 km, (d)), respectively. All these sites

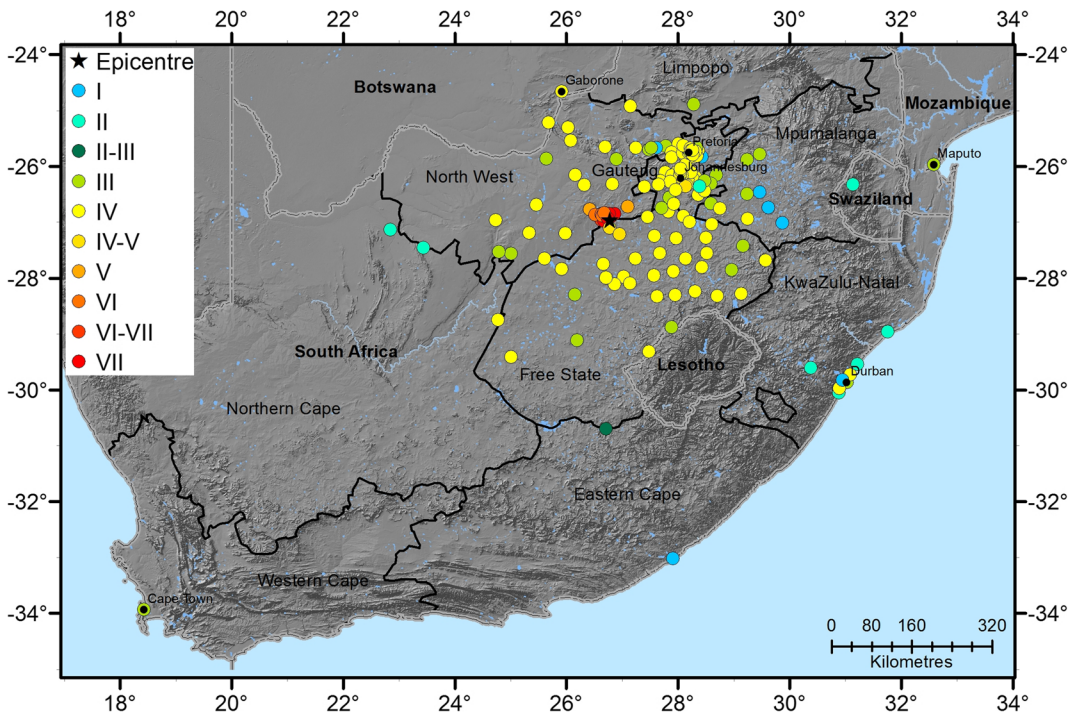

Fig. 6 The spatial distribution of IDPs obtained after the 5 August 2014 Orkney earthquake. The *black star* indicates the location of the earthquake

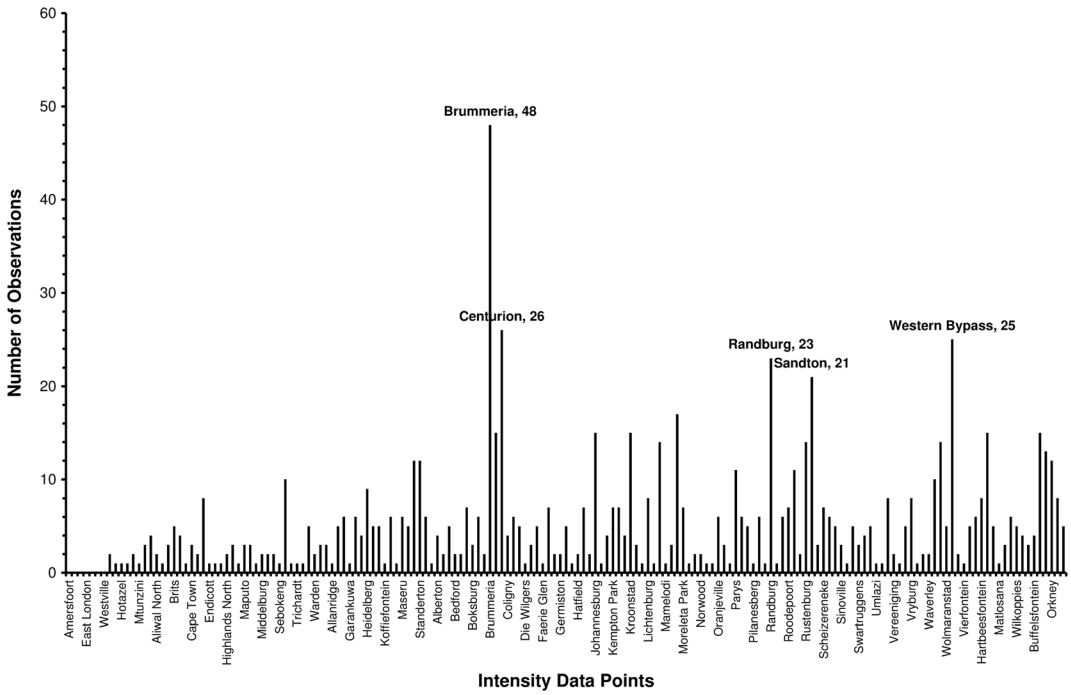

Fig. 7 Number of observations used to create each IDP

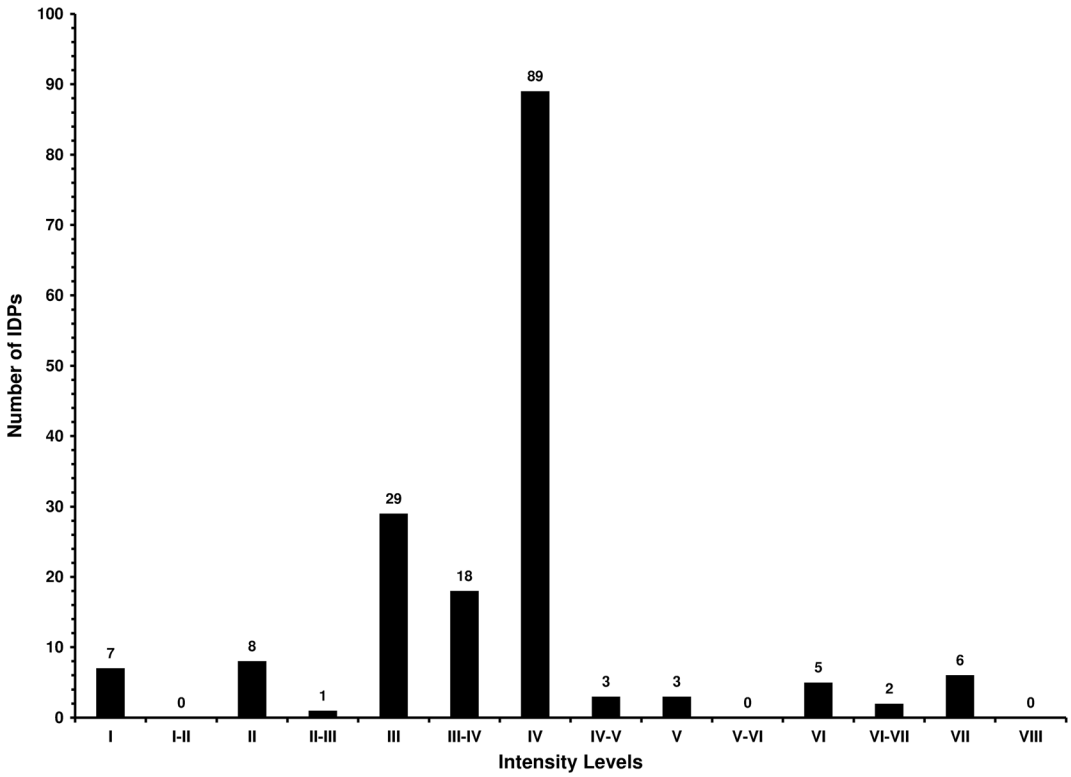

Fig. 8 Number of IDPs obtained for each intensity level

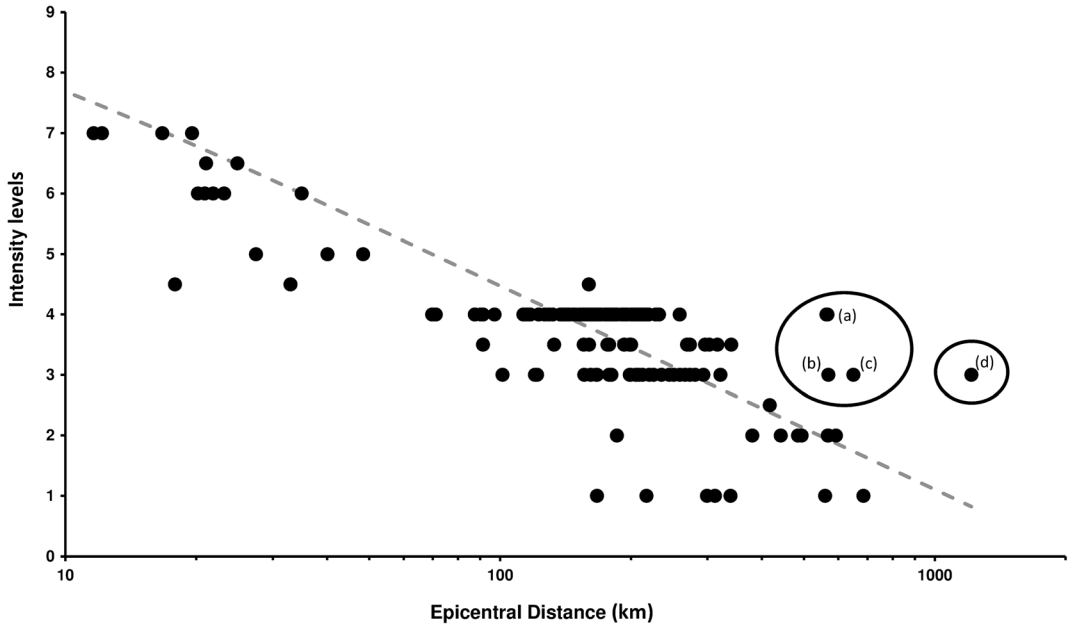

Fig. 9 The intensity–distance plot for the IDPs obtained for the main 5 August 2014 Orkney earthquake. The *broken grey line* represents the modified Bakun and Scotti (2006) intensity–distance model (Eq. 1)

are located along the coast, implying that thick soil layers beneath the cities could have resulted in the amplification of the ground motion. The amplification of ground motion at Durban is seen consistently for large regional earthquakes, such as the 22 February 2006 Machaze, Mozambique, earthquake, where shaking of intensity value MMI=III was observed (USGS 2006).

The IDP intensity–distance distribution is compared with a modified Bakun and Scotti (2006) model which

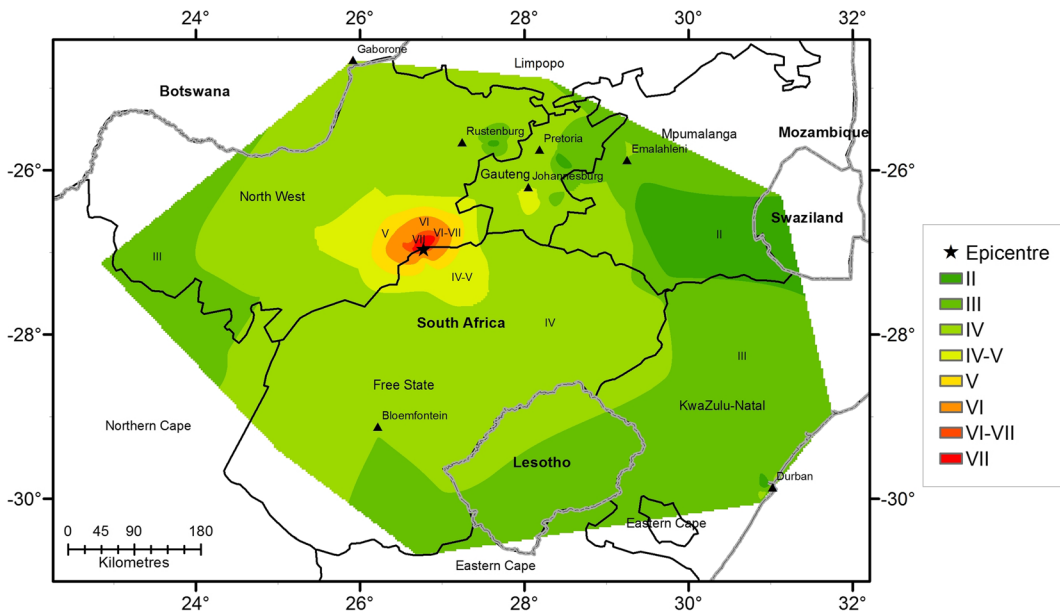

Fig. 10 An isoseismal map of the earthquake of 5 August 2014, which shows *bands of colours* of equal intensity. The epicentre of the event is shown as a *black star*

was prepared for the French stable continental region. The modified model has the following formula:

$$I = 4.08 + 1.27M - 3.37 log \Delta_h \quad (1)$$

where M is the earthquake local magnitude and Δ_h is the epicentral distance in kilometres. The decay of intensity values with distance fits the shape of this modified French model well and clearly shows the effect of attenuation of the ground motion, especially for the region between 20 and 600 km.

2.2 Isoseismal map

An isoseismal map was created using the obtained intensity values and presented in Fig. 10. The values were gridded using the natural neighbour interpolation technique (Sibson 1981) to create the map in which lines are used to join positions of equal intensities. The warmer colours indicate higher intensities up to VII, and the lower intensities are indicated by the colder colours. Thus, areas are shaded using the same colour to indicate that they experienced a similar intensity of shaking. The estimated mean isoseismal radii for the zones VII, VI–VII, VI and V are 12, 23, 33 and 54 km, respectively. The epicentre is located in the southeast part of the zone that experienced the strongest shaking (intensity VII). The apparent displacement of the zone to the northwest of the epicentre is because most of the settlements close to the epicentre are located in that direction. Moderate damage was observed on houses in the towns/communities in this region. Shaking of intensity level IV was felt as far as Pretoria, western parts of Lesotho and southeastern parts of Botswana. Some sections of Johannesburg (CBD and northern suburbs) unexpectedly experienced shaking of even higher intensity (IV–V). An explanation for this could be that the high intensity values at long distances are amplified by site effects such as local geology and/or topography as has been observed in many places (e.g. Faccioli et al. 2002; Boore 1972; Celebi 1987, 1991; Ashford and Sitar 1994; Athanasopoulos et al. 1999).

3 Conclusions

Intensity values were assigned to create IDPs for the 5 August 2014 Orkney earthquake using observation data collected mainly from information collected on questionnaires submitted online to the CGS and others filled in during interviews conducted by CGS personnel. Some of the observations were also obtained from stories and comments in newspaper reports and online social websites like Twitter. A total of 170 IDPs were created, with the highest intensity level of VII experienced in several towns located near the epicentre. Observations indicating felt effects of the event were obtained from as far as Cape Town, Maputo, Gaborone and Durban. Higher than expected intensity values were also experienced in Johannesburg central and northern suburbs, as well as in Centurion to the north. It is clear that site effects contribute much to the distribution of the observed intensities. Further investigations on the attenuation of these intensity values are necessary and also to compare them to measured strong ground motion. An investigation of the aftershock sequence is also essential to understand better the source of these events.

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