LOCAL EARTHQUAKE DETERMINATION AND SEISMIC HAZARD IN BOTSWANA

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February, 2017

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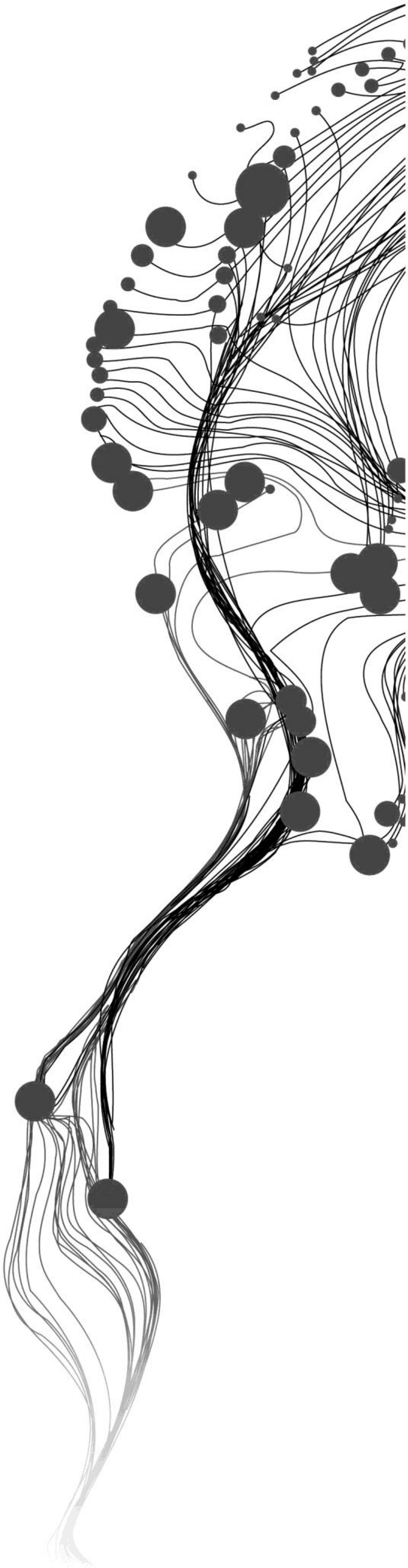

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HARRISON SILITO FORD MTUMBUKA
Enschede, The Netherlands, February, 2017

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Applied Earth Sciences – Natural Hazards, Risk and Engineering

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ABSTRACT

Botswana experiences earthquakes of various sizes (magnitude) owing to the country's geographical location within the East Africa Rift System with the highest magnitude event recorded in 1952. Reports indicates that this M = 6.7 caused damages. Despite the existence of these records and the continued recordings of seismic activities in the country, seismic hazard studies at country level have not been carried out which means that seismic hazard levels for different parts of the country are not known. This study was meant to therefore fill this knowledge gap.

381 earthquake records were collected from various agencies, compiled into single earthquake catalogue; magnitudes homogenised to single local magnitude and catalogue completeness checked. A methodology was established to identify and delineate seismic source zones. This resulted into the delineation of 15 zones which were effectively used in the hazard analysis.

Seismic hazard results analysed for 10% probability of exceedance in 50 years lifetime identified Maun area within Botswana to have high level of hazard. Gaborone in the south and other parts of the country were found to have lower levels of peak ground acceleration. The hazard level was found to be highest in the area south of Gaborone in South Africa. However, from the result it is apparent that not all seismic zones are active in the hazard computation except for a only five zones. Nonetheless, this research has contributed knowledge in the area of seismic hazard in Botswana at the same time it has opened up more room for further research in the area.

ACKNOWLEDGEMENTS

My first thanks goes to my supervisors Professor Mark van der Meijde and Dr. Olga Mavrouli, for always being there for me whenever am stuck or need your guidance. Also thanks to my advisor, Islam Fadel, for your assistance especially in the area of programming..

I wish to thank the Malawi Government through the Department of Human Resource Management and Development for financing my Msc study. And specifically I wish to thank the management of the Geological Survey Department for endorsing my name to undertake this graduate training. Thank you.

Also, I must express my very profound gratitude to my wife Regina Kamowa and my son Hope Mtumbuka for providing me with unfailing support and continuous encouragement throughout my duration of my study. I hope this thesis can represent reason of pride for my parents, and as motivation for my brothers and sisters.

Finally, I wish to thank the God Almighty for His grace and fulfilment of His promise. Indeed your peace, God transcends all our understanding (Philippians 4:7).

LIST OF ABBREVIATIONS

Agency code	**Agency name**
PRE	Council for Geoscience, South Africa
BUL	Goetz Observation, Zimbabwe
ISC	International Seismological Centre
EAF	Eastern African Network, Unknown
USGS	United States Geological Survey, United States
LSZ	Geological Survey Department of Zambia, Lusaka
NAM	The Geological Survey Deaprtment of Namibia, Namibia
IDC	International Data Center, CTBTO, Austria
CNG	Seismographic Station Changalane, Mozambique

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1. INTRODUCTION

1.1. Background

Worldwide, earthquakes are among the most devastating natural hazards that lead to astronomical loss of lives and livelihoods. According to Giardini et al., (1993), the vulnerability to disaster is mainly on the rise due to increasing urbanization and developments taking place even in zones that are prone to damaging earthquakes. In order therefore to reduce the loss of life, property damage and social economic disruption resulting from earthquakes, it is important to carry out a seismic hazard estimation which guides various stakeholders including engineers and policy makers in land use planning, improved building design and construction.

Seismic hazard, which is the probability of experiencing a specific ground shaking at a specific site or region due to earthquakes (Elnashai et al., 2015), can be evaluated using two methods; the deterministic approach and the probabilistic approach. In the deterministic seismic hazard approach, only a single event (mostly, worst case scenario) from an earthquake catalogue is considered and also the shortest distance from the site to the closest source is taken into account. This method is preferred in the assessments for big engineering projects such as nuclear power plants and dams. On the other hand, probabilistic seismic hazard approach considers all events in a catalogue, all possible sites to source and combines uncertainties arising in the probability computations. This method is popular in seismic hazard analysis at different scales ranging from global studies (Shedlock, 2000; Giardini, 2003), regional studies (Midzi, 1999; Zhang, 1999; Woessner et al., 2015), and country level (Badawy, 2016; Mapuranga, 2014; Sitharam, 2015). This therefore makes this approach suitable for use in Botswana.

A number of regional seismic hazard studies have been carried out in Africa with the Global Seismic Hazard Assessment Programme (Midzi et al., 1999) being the most prominent one. The research covered an area within latitudes 40^{o} S and 25^{o} S and longitudes 10^{o} E and 55^{o} E on which a catalogue covering a time period 627 – 1994 was used. Using the probabilistic seismic hazard analysis approach, the resulting Peak Ground Acceleration (PGA) indicated relatively high hazard along the East African Rift System. In the northern half of the rift system the PGA values exceeded 250 gals for 10% probability of exceedance in 50 years (Figure 1). However, due to the vastness of the areas under consideration in such regional studies, often times the outcomes could not be reliably used at a local scale as they do not take into consideration all important local features including local seismicity and faults.

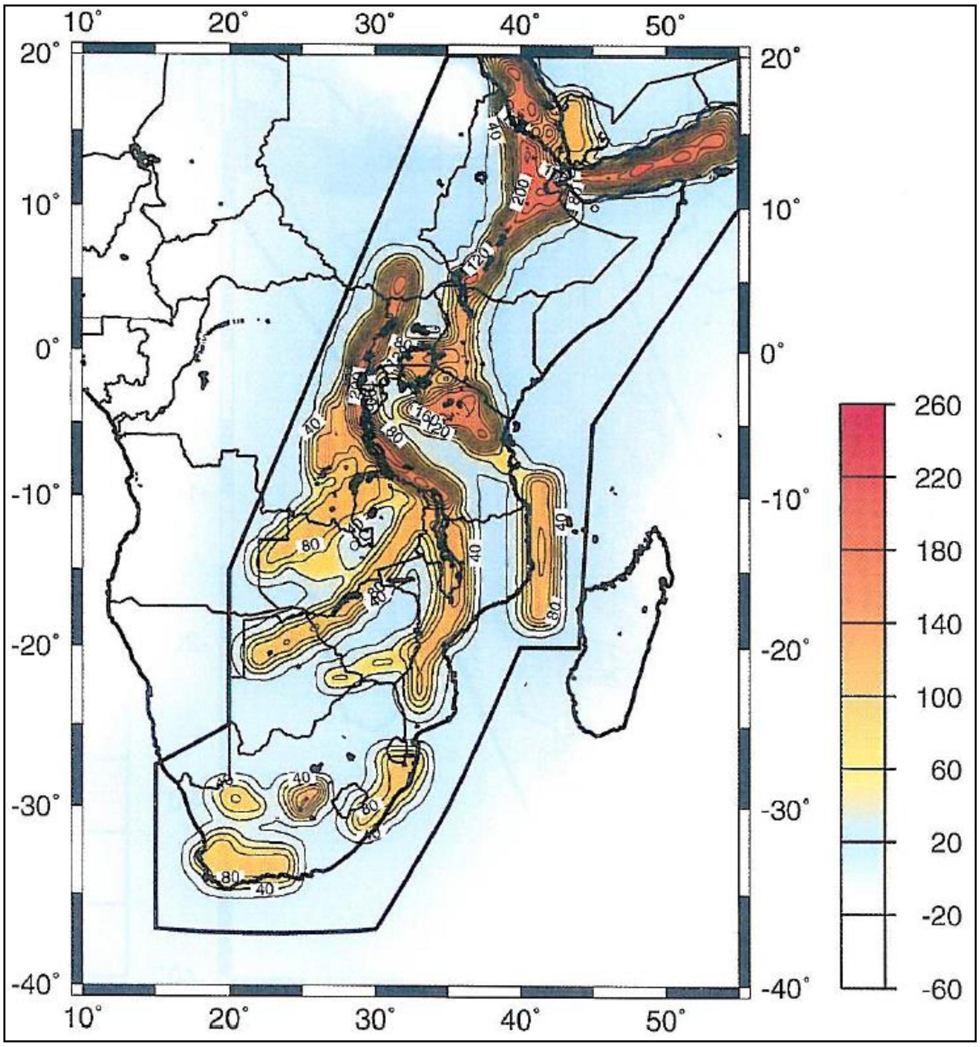

Figure 1: Distribution of mean Peak Ground Acceleration (in gals) values in Eastern and Southern Africa computed for 10% probability of exceedance in 50years (contour interval is 40 gals)

Previous seismic hazard studies in Botswana are almost none existence. This is evident by the scarcity of data on the same. However, according to Reeves (1972) and Hutchins et al., (1976), an assessment that was carried out following the two 1952 earthquakes of Richter magnitudes 6.1 and 6.7, found that the events had damaging consequences. For example, at Maun, which is an area about 40 km north of the epicentres, damaged buildings were reported. It has further been suggested that these events affected the geomorphological landscape of the area leading to changes in the drainage pattern in the Okavango Delta (Pike, 1970). Overall, Reeves (1972), concluded that continued earthquake activities in Botswana posed little or no threats to humans as the country is generally flat and largely unpopulated. The current research plans to check the spatial variations of seismic hazard for Botswana and the result of which would be helpful to planners and policy makers when it comes to formulation of building codes in the country.

An assessment of the seismic hazard for Botswana will be undertaken following the Probabilistic Seismic Hazard Analysis (PSHA) approach. PSHA in general follows 4 main steps; (1) identification of seismic activity and corresponding source zones; (2) characterization of each source; (3) identification of the peak ground attenuation relationships and; (4) all the three points are combined to calculate a seismic hazard map.

1.2. Problem statement

Botswana is a country with a history of seismicity, with the highest magnitude earthquakes recorded in the 1952. However it comes as a surprise that in a country with such earthquake occurrence background there have been no studies carried out to determine the seismic hazard of the various areas. In undertaking hazard analysis, records of seismicity are needed. The Council for Geosciences of South Africa publishes quarterly seismological bulletins which combines data obtained from various seismological stations in the region. These bulletins are accessible online free of charge. The availability of such data therefore provides a good opportunity for the compilation of an updated earthquake catalogue for Botswana to be used for the hazard analysis.

1.3. Research objectives

The main objective is to assess levels of seismic hazard in Botswana's and better understand the seismicity of the country. The following are the specific objectives:

1. To compile a seismic catalogue for Botswana from different sources
2. To perform magnitude homogenization
3. To derive seismic source model based on geological and seismological data that describe the potential locations of future earthquakes within the study area
4. To evaluate characteristic recurrence relationships for various defined source zones
5. To determine suitable ground motion prediction equations (GMPE) for use in seismic hazard analysis
6. To analyze earthquake instrumentation data for Botswana and locate earthquake epicentres for updating earthquake catalogue

1.4. Research questions

1. What is the appropriate magnitude type to be used for the homogenization process? What are the magnitude transformation relations to be used in magnitude homogenization?
2. What are the uncertainties related to the input seismic data for the hazard assessment?
3. What should the output of the hazard map represent?
4. What insight will the hazard map of Botswana give in relation to the tectonic activities of the country?
5. Is there any pattern in terms of the locations and depth distribution of local earthquakes in the country?

1.5. Local earthquake determination

This research broadly comprised two parts; location of local earthquake in Botswana from instrumentation data for updating the catalogue and computation of the seismic hazard based on the updated catalogue. The latter has been pursued in detail in this research. On the former, which addresses specific objective and research question 5, a python programming code for processing seismic data was established in OBSPY in ANACONDA software and some earthquakes were effectively identified and located using HYPOELLIPSE software. The generated code, files used to compile HYPOELLIPSE and other results in this process are in **Appendix A**. Unfortunately, this is how far this research pursued this objective because of time constraints; however it is a good area for further research.

1.6. General methodology

The research was carried out in four stages Figure 2. The first stage involved collection of seismic data for the study area from online sources such as the USGS, the CGS and the ISC. The collected seismic data was then compiled into a seismic catalogue. Stage two involved computation of epicentre density and magnitude density from the seismicity data, giving scores (weightage) to the resultant maps and finally delineation of seismic source zones. Stage three involved extraction of epicentres falling within each delineated source zone and characterisation of each source zone. Lastly, in stage four the Gutenberg – Richter parameters for each source zone was combined with ground motion attenuation model to obtain the hazard map.

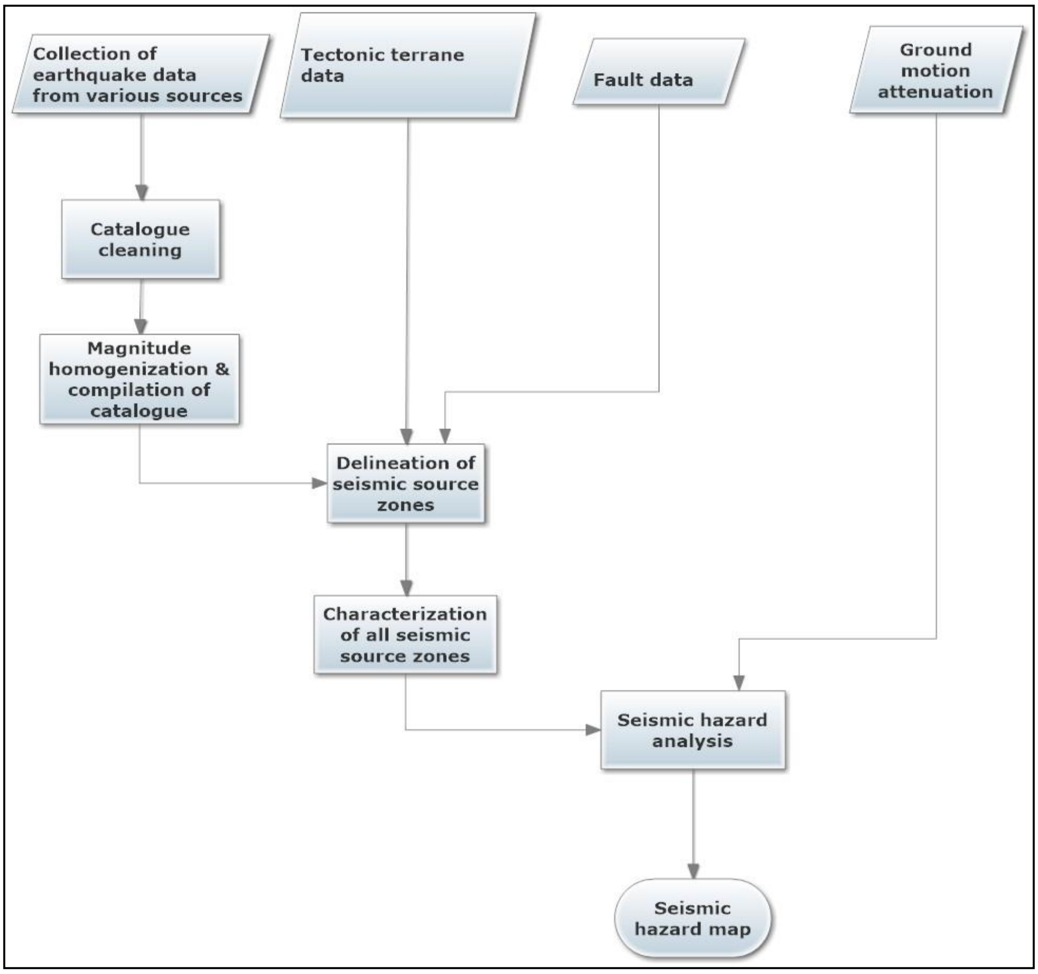

Figure 2: General methodological flow chart followed in this research

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2. STUDY AREA

2.1. Location of Study area

Botswana, which is located in southern Africa, has a total area coverage of 581, 730km^2. It is bounded by latitudes -18^0 and -27^0 North and longitudes 20^0 and 29^0 East Figure 4. The country has diverse geological formations and tectonic history. The former, however has been obscured in most parts of the country by the Kalahari sands (Reeves, 1972; Hutchins, et al., 1976; Kinabo, 2007; Modisi, 2000; McCarthy, et al., 1993; Gumbricht, et al., 2001). Nonetheless, many studies carried out in the country have circumvented this hindrance through the employment of different techniques such as:

- High resolution aeromagnetics and gravity surveys (Kinabo, 2007),
- Remote sensing imagery (Kinabo et al., 2007)
- Routine geological mapping by Botswana Geological Survey with associated drilling (Carney et al., 1994 & Key et al., 1999),
- Ground water exploration (Zeil et al., 1991) and regional airborne geophysics survey (Hutchins et al., 1980) and geochronology data (Singletary et al., 2003).

2.2. Tectonic setting

2.2.1. The East Africa Rift System (EARS)

The East Africa Rift System (EARS) in a broader sense consists of 2 branches; the Eastern branch that roughly cuts through Kenya; and the Western branch, which extends northwards from the northern end of Lake Malawi (Figure 3). These feature have already been well studied by numerous researchers (Jones et al., 1979; Corti, 2009; Oxburgh, 2015; Harðarson, 2014; Roberts et al., 2012; Ebinger, 1989; Chapola, 1997; Mulibo, et al., 2016; Saemundsson 2010). Saemundsson (2010) observed three peculiar characteristics associated with the EARS particularly; (1) it is a seismically active zone; (2) it is dominated by normal faulting and; (3) seismic data shows predominantly shallow earthquakes (focal depth of 12-15km beneath axis). However, comparison between the two branches shows that the Western branch is more seismically active than the Eastern branch (Saemundsson, 2010). Another branch has been discovered in the western part where it extends southwest from Zambia into northwest of Botswana and is called the Southwestern branch of the East Africa Rift System.

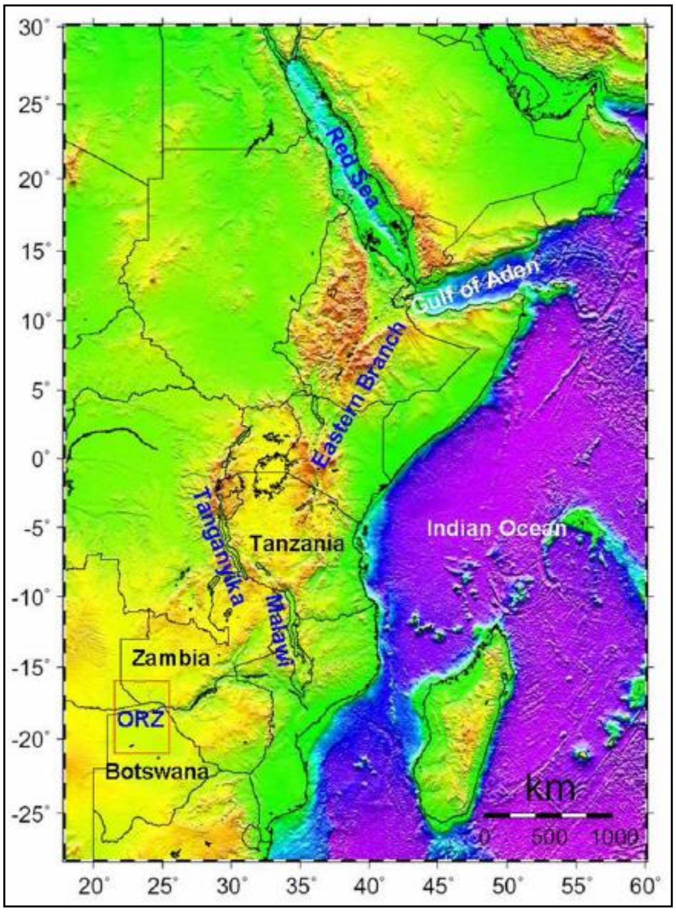


Figure 3: SRTM DEM map of the EARS showing the Okavango Rift Zone ((Kinabo, 2007), p55)

2.2.2. Southwestern branch of the EARS

Primarily this branch of the EARS extends from Zambia to southeast Congo before terminating into the southwestern part in Botswana (Reeves, 1972). It is associated with basins and wide valley which are typical features of the EARS. According to Kinabo (2007) this branch is associated with a network of isolated less defined quaternary rift basins that are distributed along an approximately 250 km wide zone extending for about 1,700 km west of Lake Tanganyika and Lake Malawi with the Okavango Rift Zone (ORZ) at its southern end (Figure 3).

These associated rift have an average length of about 100km and are about 40-80 km in wide (Modisi, 2000) and they include; 3 Luangwa, Luano, Mweru and Lukusashi (in Zambia), Upemba (in Democratic Republic of Congo), and Okavango (in northwest Botswana) (Kinabo, 2007).

The Okavango basin in northwest Botswana is one area that has been subjected to a number of studies by various researchers with the aim of understanding the early development of the young rift system (Modisi, 2000; Kinabo, 2007; Scholz, 1997; Kinabo et al., 2007a; Hutchins, et al., 1976; Bufford et al., 2012; Reeves, 1972). This young rift system is popularly known as Okavango Rift Zone (ORZ). The stress forces experienced during the formation process of the ORZ led to the formation of major northeast – southwest faults which are Tsau, Lecha, Kunyere, Thamalakane, Phuti, Nare and the Sekaka Shear Zone (Kinabo, 2007). From the geophysical investigations by Kinabo et al., (2007), two forms of fault displacement were identified. First is the southeast dipping normal faults which include Tsau, Gumare and Lecha. Secondly, the northwest dipping faults like Kunyere, Thamalakane, Phuti, Nare, Mababe, Linyati and Chobe. Kunyere Fault is the boundary fault of the rift zone in the south while the Mababe Fault forms the boundary in the north (Kinabo, 2007).

Most of the earthquake occurrences in Botswana are associated with normal faulting system. According to Hutchins, et al., (1976) a composite focal mechanism of the Okavango area from well-located events in the area indicates normal faulting along planes dipping 60^o to the north-west. The seismicity strongly provides evidence of the rifting in the area. On the other hand, the seismicity in the Kalahari seismicity axis (Reeves, 1972b) is a reflection of subsidence in the region mainly because the lowest area of the Kalahari basin falls astride the axis and the drainage system in the Kalahari conforms to north-east strike bias. However, despite the seismicity associated with the Kalahari axis, the feature is not part of the East Africa Rift System (Reeves, 1972b).

Botswana experienced a collision of cratonic blocks which happened along tectonic belts between 2.9 – 1.2 billion years ago (Chisenga, 2015). The main cratonic blocks in the country which also form the basement rocks are the Kaapvaal and Zimbabwe Cratons (Figure 4). The Kaapvaal Craton formed, about 3.5 billion years ago (James, 2003), as a result of collision between the Kraaipan arc and the continental margin and extends westwards underneath the Kalahari rocks in southeast of Botswana (Haddon, 2005). On the other hand, the Zimbabwe Craton which formed during the period 3.55 – 2.58 billion years ago (Dirks & Jelsma, 2002), extends westwards into the eastern part of Botswana. These two Archaean stable blocks of the earth's crust are separated by the Limpopo mobile belt.

Kheis Belt, which is 2000 million years old, is a zone of low-grade metasedimentary and volcanic rocks and marks the western boundary of the Kaapvaal Craton (Schlüter, 2006). This belt extends northwards into southern Botswana forming a tectono-metamorphic transition zone between the stable Kaapvaal Craton to the east and high grade metamorphic rocks of the Namaqua-Natal Belt to the southwest and west.

The Magondi Belt formed in the early Proterozoic period and is estimated to have been formed 1997.5±2.6 million years ago (Haddon, 2005). The age represent the main age of the main phase of deformation of the Magondi Belt. The belt marks the western margin of the Zimbabwe Craton, depicting the transition of a passive-margin setting into geosynclinals deposits. It is characterized by rocks of the Magondi Supergroup. These rocks were initially deformed around 2000-1800 Ma and again at ~820 Ma (Haddon 2005). To the northwest the Magondi Belt is bounded by the Mesoproterozoic northwest Botswana Rift and the inland arm of the Neoproterozoic Damara Belt.

The Ghanzi-Chobe Belt was formed by extensional tectonic forces associated with a continental collision along the Namaqua-Natal Belt (Modisi, 2000). The dimensions of the belt have been constrained to 500 km long and 100 km wide in western and northern Botswana consisting of volcano-sedimentary lithologies (Rankin, 2015). Ghanzi-Chobe Belt is tectonically bounded by the Pleistocene Okavango Rift in the northwestern part of the zone (Carney et al., 1994).

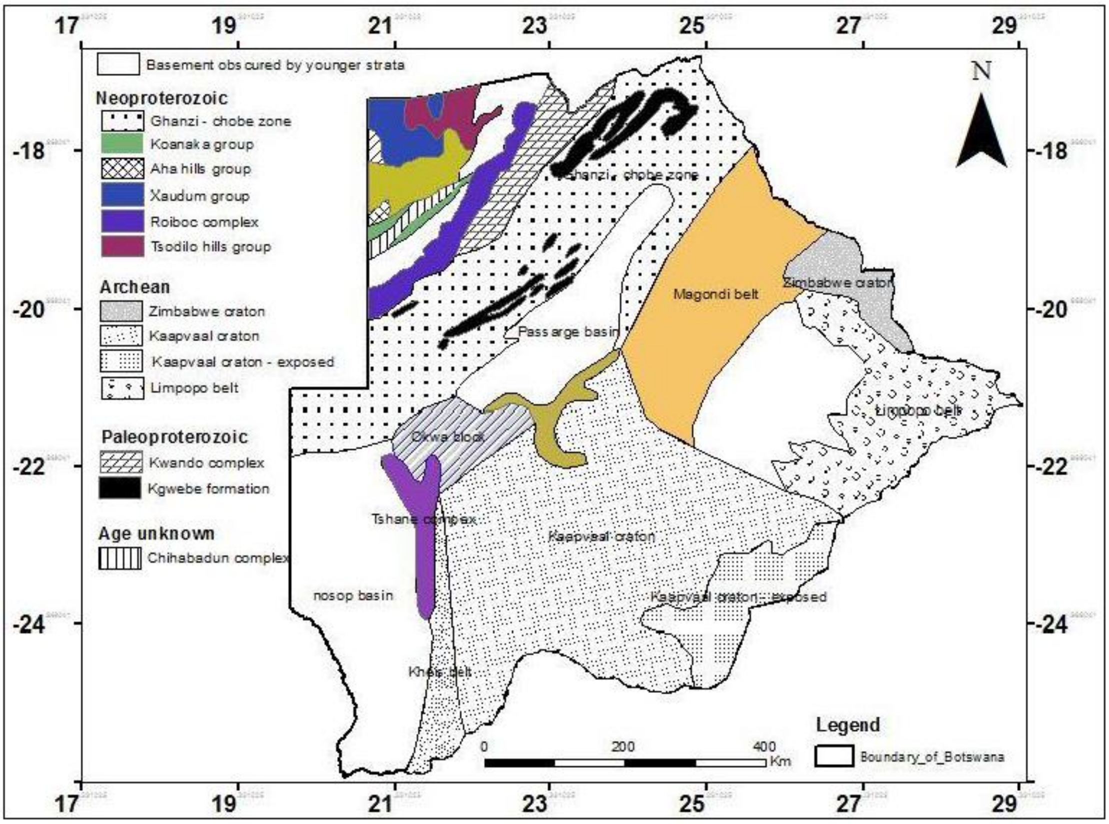


Figure 4: The Basement geology of Botswana (Singletary, 2003)

2.3. Seismicity

Study of seismicity undertaken in Botswana has shown that the country is seismically active. This came into the limelight following the publications of earthquake epicenters for the country for the years between 1965 and 1971 which were recorded by the Zimbabwe seismograph network (Reeves, 1972b). However, seismicity is not uniformly distributed in the Botswana. Reeves (1972) in his analysis of the published epicenters identified two distinctively spatial clusters of epiceters; (1) a dense cluster over the Okavango Delta area, in the northwest of the country and; (2) a broadly scattered belt of epicenters trending north-east in the central Kalahari basin (Figure 5).

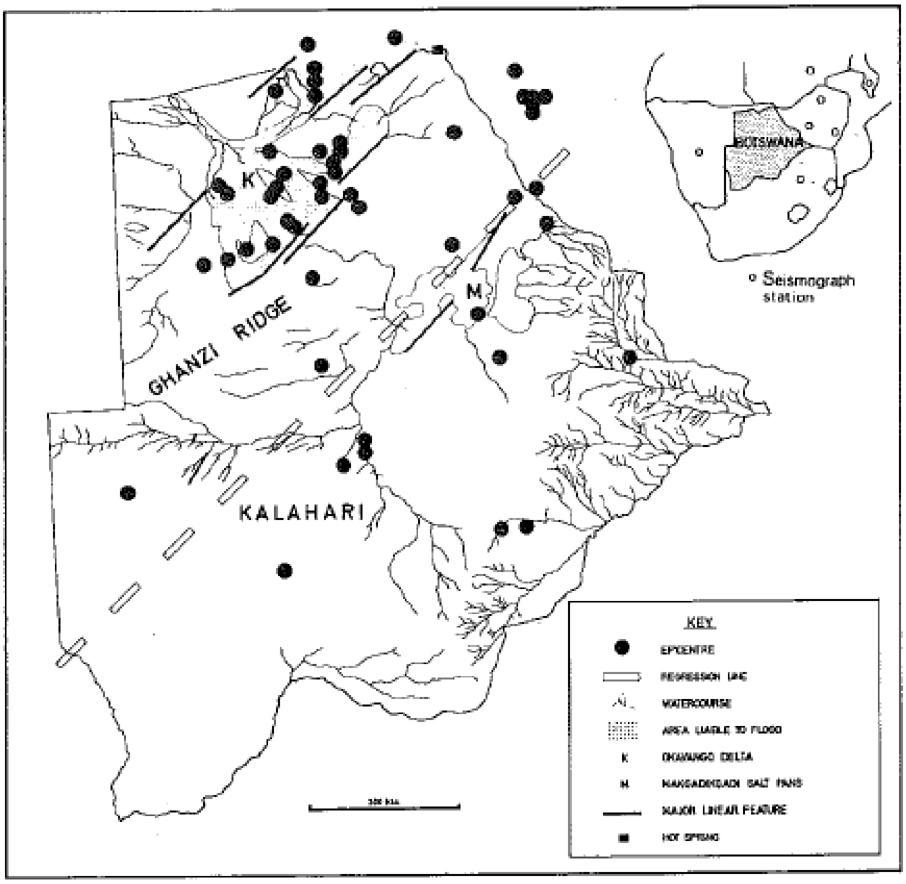


Figure 5: Earthquake epicentres in Botswana based on 1965 to 1971 data (Reeves (1972), p95).

These events were of varying Richter magnitudes wherein the highest magnitudes 6.1 and 6.7 were recorded by a network of seismograph in neighbouring South Africa in 1952. The South African seismic network came into operation in 1910 which was upgraded in 1971 (Malephane, 2007). However, Botswana's over reliance on regional seismological network meant that only higher magnitude events could be detected at such far distances between the station and the site and also there are inevitably high location errors.

3. DATASET

This research used earthquake data which was compiled from different sources for events that have epicentres located within Botswana (for all magnitude sizes) as well as higher magnitude events (M ≥ 5) located outside the country's border.

3.1. Earthquake Data

Earthquake data, which is one of the inputs in the hazard analysis, was collected from various sources for the purpose of compilation of earthquake catalogue. Source of data included seismological bulletins from online databases such as the Council for Geoscience (CGS) of South Africa, the International Seismological Centre (ISC), and the United States Geological Survey (USGS). In addition to bulletins, earthquake data were also derived from literature (Reeves 1972). The combined data covers the period 1952 - 2016, and also include 20 events of M ≥ 5 for earthquake epicentres located at a determined distance of 200 km from the Botswana border. Earthquake data derived from the CGS bulletins covered the period 2010 to 2016 while data for the period 1952 to 2014 was derived from the USGS. And for the period 1952 to 2011, the data was derived from the ISC. A total of 395 records were initially compiled, 96% (381 events) of the earthquake records had been reported in different magnitude scales, whereas 4% (14 events) of the earthquakes had no magnitude assigned (Figure 6).

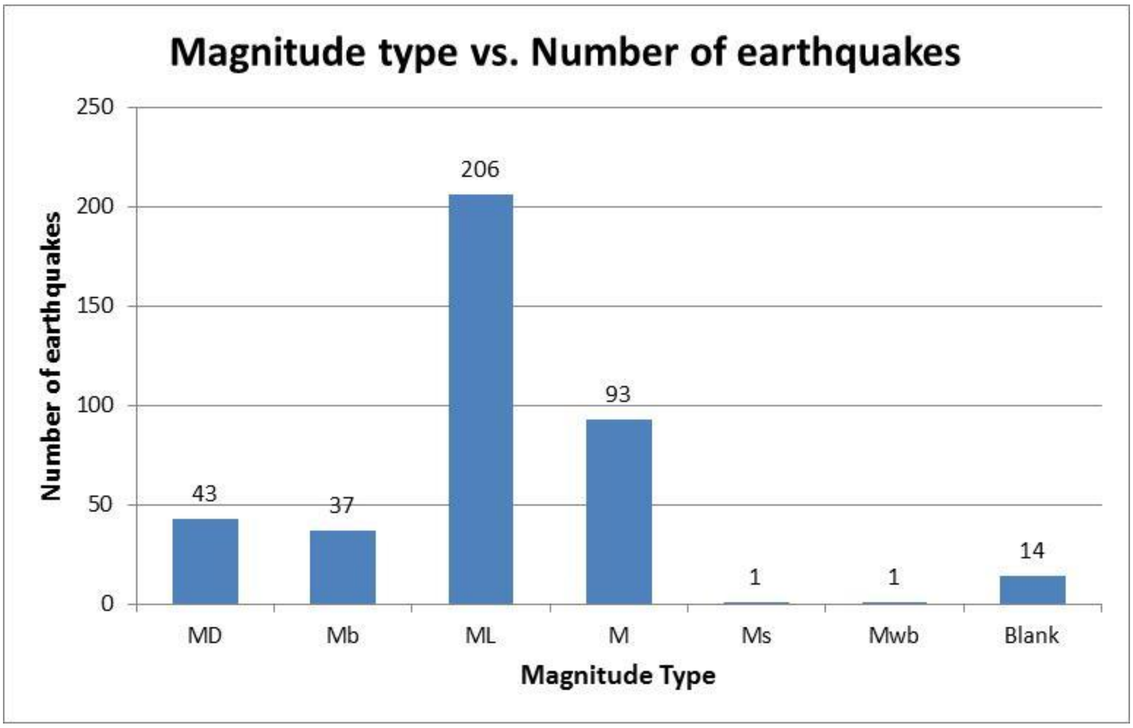


Figure 6: Distribution of different magnitudes compiled in the catalogue derived from different sources for the study area. Magnitude type MD = Duration magnitude; Mb = Body magnitude; ML = Local magnitude; M = Unspecified magnitude type often related to real or near-real time magnitude (ISC, 2010); Ms = Surface magnitude; Mwb = Moment magnitude; Blank = Records missing magnitude.

Two records of highest magnitude earthquakes that happened in 1952 within Botswana were derived from the literature by Reeves (1972). According to available literature, both earthquakes of Richter magnitude M = 6.7 and M = 6.1 occurred on 11th of October and 11th of Septermber respectively in 1952 (Reeves 1972). However the author did not provide the actual time when events occurred and most importantly the latitudes and longitudes for location. Therefore, these missing parameters were adopted from the USGS which reported the same events in moment magnitude scale. The reasons why Richter magnitude was preferred in this instance have been provided in the next section.

The majority of the events (about 53%) were reported by the Council for Geoscience in Pretoria, South Africa while the remaining 47% of the records were reported by various agencies including BUL, ISC, EAF, USGS, NAM, IDC, LSZ, CNG (see Appendix 1 for full names of these agencies' codes).

3.2. Earthquake catalogue clean-up

A rigorous catalogue cleaning process was carried out in order to remove records with blank magnitudes, duplicate records and suspected induced earthquakes from the catalogue. This process preceded the magnitude homogenisation process. In this process, two events were considered to be the same if they described earthquakes that lie within a time frame of 20 seconds and a space frame of 50 km from each other (Suckale et al., 2005).

Moreover, since no established criteria for determination of mine-induced seismicity was found, a criterion was established to remove suspected induced events from the catalogue. First 10 km was considered as a reasonable distance within which all events occurring therein would be attributed to mining activities. Further it was observed from the CGS bulletins that most reported mining related events have magnitude in the range of range from M = 1.4 to M = 2.7 and depth of 5 km and below (Council For Geoscience, 2016). Therefore the cut-off magnitude threshold for events to be considered mining related was M>2.8 and less than 5 km depth. Following this criteria, 3 records were identified and removed from the catalogue. All these processes were performed in Microsoft's Excel sheet and ArcGIS software. After the cleaning process, 14 records without magnitudes and 31 duplicate records were deleted from the catalogue resulting to the final catalogue with a total of 381 events.

3.3. Earthquake spatial distribution

An epicenter map of Botswana for earthquakes of ML ≥ 1.0 is shown in Figure 7 for the period 1952 - 2016. From the figure it is evident that epicenters are mostly clustered in the northwest part of the country (in the Okavango Delta area close to Maun) where the two Richter magnitudes 6.1 and 6.7 are also located. Seemingly another cluster of relatively larger epicenters can be seen in the southeast of the country while sparsely populated epicenters are located in the central Kalahari basin area, southwest and northeast. It can be noted however; the absence of epicenters around the Ghanzi area and the immediate area to the south could be attributed not to the absence of earthquake activities but rather lack of seismic network which could effectively be used. This would lead to underestimation of the hazard for the area.

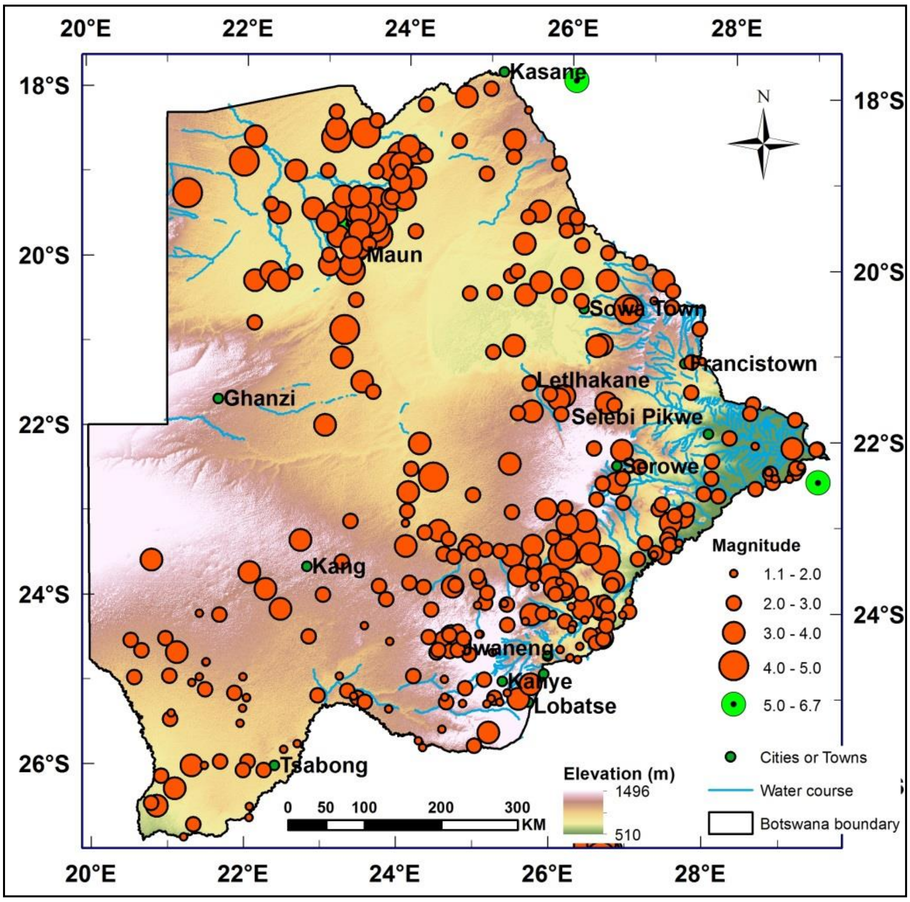


Figure 7: The SRTM DEM map for Botswana and superimposed are the earthquake epicentres.

4. METHODOLOGY

The methodology implemented in this research is summarised in this section in the methodological flowchart in Figure and further explained below.

4.1. Homogenisation of magnitudes

Seismic hazard is dependent on spatial and temporal earthquake distribution in the area (Chapola, 1997). The diversity in which different agencies determine earthquake magnitudes makes the process difficult unless all homogenisation of magnitudes into one chosen type takes place. This is because the various magnitudes displayed in Figure 6 displays different levels of saturation effects at different magnitudes (Mapuranga, 2014). In this study, the local magnitude scale (ML) was selected. ML magnitude scale was chosen particularly because majority of the earthquakes, 52% (206 earthquakes) in the catalogue have been reported with ML (Malephane, 2007). Also ML magnitude is applicable measure for small and shallow earthquakes (Elnashai, et al., 2015), which is applicable to the case in the study area (Reeves, 1972). Therefore magnitude homogenisation procedure was performed as follows; (a) where ML and M magnitudes were reported, they were adopted as such; (b) all other magnitudes were converted to ML which was taken as standard.

Different conversion relations given below were used to convert different magnitudes to ML. Therefore to convert MD to ML the following relation adopted from Brumbaugh (1989) was used:

$$ML = 0.936Md - 0.16 \pm 0.22 \qquad (1)$$

To convert Mb to ML, the relationship of Chhabra, et al., (1976) was used:

$$ML = (1.00 \pm 0.57) + (0.80 \pm 0.01)Mb \quad (\Delta = 2^0 \text{ to } 10^0) \qquad (2)$$

Where Δ stands for epicentral range within which the relation was determined.

To convert Mw to ML, the model modified after (Twesigomwe, 1997) was used:

$$ML = (Mw + 4.682)/2.386 \qquad (3)$$

However, as no conversion relationship could be found for conversion of the magnitude M events which form 23.5% (93 earthquakes) of the catalogue, it was assumed that at the time of reporting, magnitude type M was equivalent to Richter magnitude ML.

4.2. Identification and characterisation of seismic sources

The first step in the probabilistic seismic hazard approach is identification and characterisation of seismic source zones. Erdik (1999) defines a seismic source as a seismically homogenous area, in which every point within the source zone is assumed to have the same probability of being the epicentre of a future earthquake. Therefore for the process of seismic source identification to be successful requires the consideration of various factors such as geologic and tectonic features, which include active faults that potentially could affect the study area (Mapuranga, 2014). The assumption being made in seismic source identification is that within each zone an independent earthquake occurrence process is taking place (Sitharam, et al., 2015).

In this study current parameters such as seismicity, magnitude, tectonic terranes and faults were used to identify and delineate seismic source zones. Seismicity and magnitude parameters played a primary role in the process, while the two data sets played a secondary role. This is because seismicity and magnitude are the truly represent the spatial and temporal seismic activities of an area while not much studies have been carried out to identify active fault and link seismicity to tectonic terranes. Figure 8 provides the methodology followed in delineation of seismic source zones.

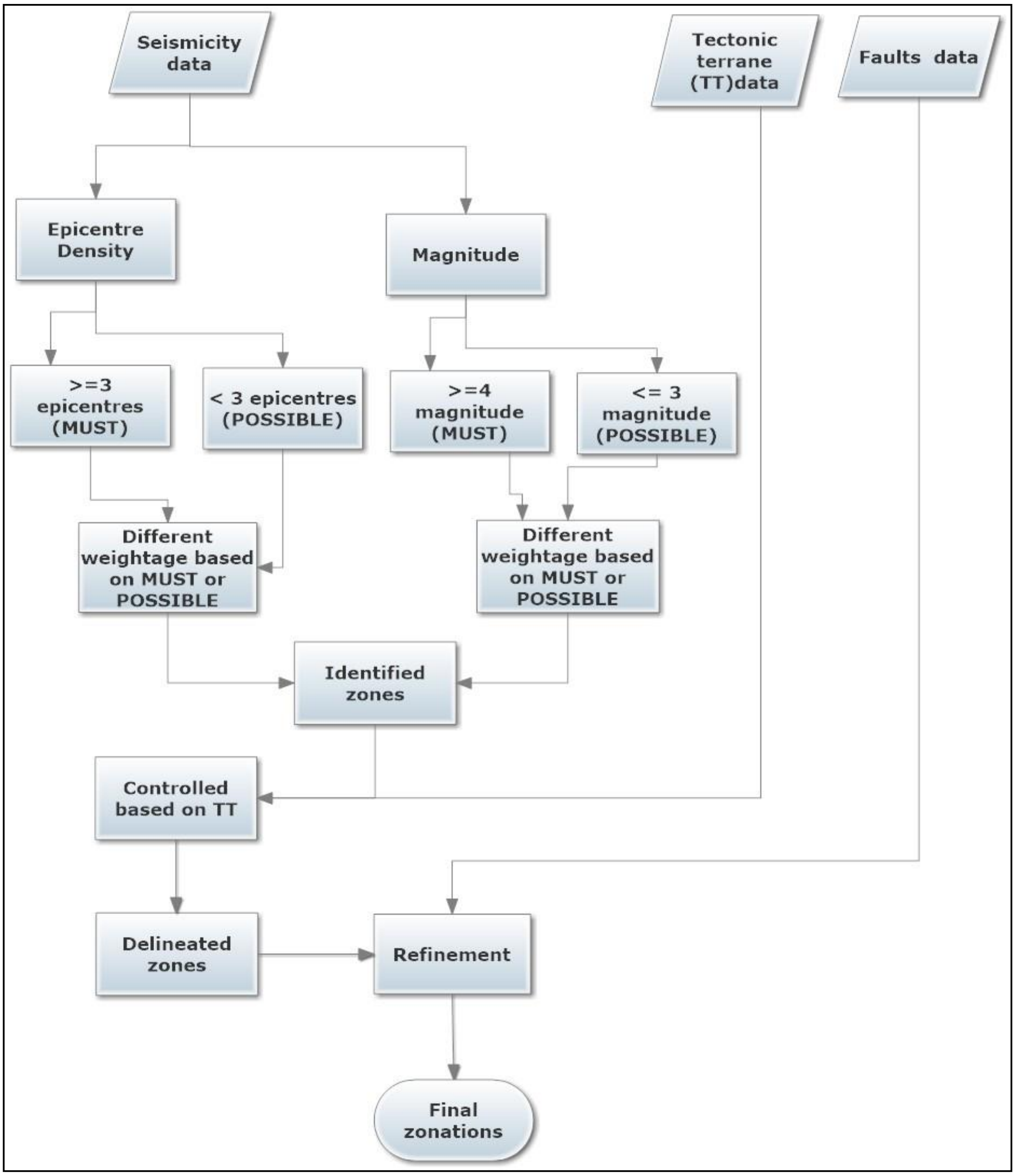


Figure 8: Methodological flow chart followed in identification and delineation of seismic source zones

The following steps were followed in the identification and delineation of seismic source zones:

1. Calculation of epicentre point density.
2. Zones with ≥ 3 epicentres were categorised as MUST include in zonation
3. Zones with < 3 epicentres considered POSSIBLE zones
4. Calculation magnitude density. Zones with M ≥ 4 within 30 km radius were considered MUST include while those with M ≤ 3 were considered POSSIBLE.
5. Binary maps were prepared where MUST zones were attributed a score of 1 and POSSIBLE zones a score 0.5 and 0.2. 0.2 was given to POSSIBLE maps with 1 epicentre with M < 3.
6. Zones were identified after summation of six weightage maps and extractive areas with total score ≥ 1and 2.

7. Zones were controlled to within tectonic terrane boundaries.
8. Delineation of zones was done
9. Superimposed delineated zones on faults to refine
10. Final source zones were derived

4.3. Determination of seismic recurrence and earthquake sizes

Under this step, the seismicity parameters such as the Gutenburg-Richter parameter b, catalogue completeness, minimum and maximum earthquake magnitude are all evaluated for each identified seismic source zone (Mapuranga, 2014).

The seismicity of each seismic source zone is characterised by several parameters. Among them, these parameters include the annual occurrence rate, b-value and a lower and upper bound magnitude for the Gutenburg-Richter (G-R) relation. The G-R relation is defined by the equation:

$$\text{Log}N(M) = a - bM \tag{1}$$

where **N** is the number of earthquakes of a given magnitude M, or larger, expected to occur during a specified period of time. **a** is the logarithm of the number of earthquakes of magnitude $M \geq 0$, expected to occur during the same time. Reiter (1990) further described **a** as the activity rate whose size depends on the overall earthquake occurrence. Lastly, b is the slope of the curve, which characterises the distribution of small to large earthquakes and is termed the b-value.

According to (Kijko et al 2012), the equation 1 is critical in seismology as it is used to describe both tectonic and induced seismicity. Application in different time scales is possible and it holds true over a large interval of earthquake magnitudes (Mapulanga, 2014).

The b-value varies within the range 0.5-1.5 depending on the tectonic environment under consideration (Scholz, 1968), however 1.0 is typical for seismically active regions. This in a way could be explained as, for a single bigger magnitude earthquake; there will be a higher number of medium magnitude earthquakes which will be followed by the highest number of smaller earthquakes. In other words, for every magnitude 4.0 event there will be 10 magnitude 3.0 events and 100 magnitude 2.0 events. Special cases occur in the value of b, and that is when dealing with earthquake swarms where 2.5 can be found, indicating a large proportion of small earthquakes to larger ones (Mapuranga, 2014). Alternatively, a b-value significantly different from 1.0 may suggest a problem with the data set; e.g. it is incomplete or contains errors in calculating magnitude (Mapuranga, 2014).

4.4. Estimating catalogue completeness

Assessment of magnitude of completeness (Mc) of instrumental earthquake catalogues is important and mandatory step for any seismicity analysis (Mignan, 2012). Mapuranga (2014) defines the level of catalogue completeness as the lowest magnitude above which all earthquakes in a space-time volume are reliably detected. Consequenlty, an earthquake catalogue could be considered complete for a given period of time if all earthquakes that occurred within that time space are accurately and comprehensively recorded in the catalogue (Wiemer, et al., 2000).

A correct estimate of Mc is crucial because a value that is too high leads to under-sampling, by discarding usable data, on the other hand, a value too low leads to erroneous seismicity parameter values and thus to a biased analysis, by using incomplete data (Mignan, 2012). In this study a plot of magnitude frequency versus time for the instrumental earthquake catalogue used in this study, was displayed to assess the catalogue for completeness (Figure 9). Visually it is observed that for the period 1966 – 2013 only earthquakes of M > 2 were recorded, indicating the incompleteness of the catalogue for events smaller than that. For the following period 2004 – 2016, events higher than 1.5 have been registered in the catalogue as well. Therefore, the completeness of the catalogue cannot be guaranteed with these observations.

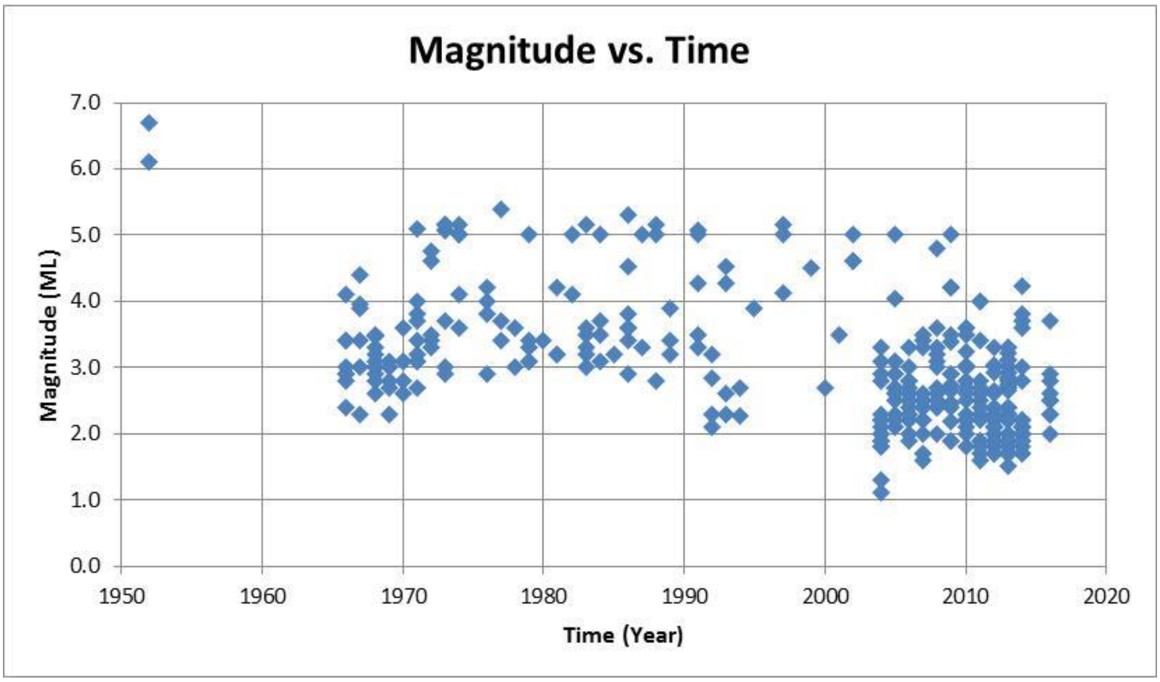


Figure 9: Magnitude distribution plot for assessment of the Botswana catalogue completeness for the period 1952 - 2016

4.5. Recurrence attenuation model

The final input required in seismic hazard analysis is the assignment of the motion estimation equation (McGuire, 1993). This equation must have 2 important characteristics; (1) the consistent magnitudes used to specify the activity rate in the seismic sources; (2) must have a distance definition consistent with the use of faults or areas' seismic sources. If areal sources are used, the ground motion equations must correctly use the distance from the point sources to the site (including the depth of energy released, i.e. the hypocentral distance).

The choice of good motion parameter should be consistent with how the seismic hazard analysis is to be used. Common parameters of interest are peak ground acceleration (PGA), peak ground velocity (PGV), and spectral velocity (SV) for a specified damping and structural frequency (often between 1 year and 25Hz) (McGuire, 1993). For horizontal components the usual procedure is to estimate the amplitude for a random horizontal component, other than the larger of 2 orthogonal components placed at random azimuths.

For this research an in-built attenuation model in CRISIS2015 was adopted and applied for to all the source zones.

5. RESULTS AND DISCUSSION

5.1. Identification and delineation of seimsic source zones

For seismic hazard analysis to be carried out, seismic sources have to be available. The process of seismic sources delineation divides the study area into zones which have relatively uniform seismicity. In some cases areas have already existing sources zones which can easily be adopted and modified before usage. However, such is not always the case. Botswana is one place which lack established seismic source zones and hence in this study, a task was undertaken to identify and delineate zonations for use in the hazard analysis. To fulfil this objective, seismicity data, tectonic terrane data and fault data were all used to derive these zones.

In the first step analysis of seismicity data in order to derive zones was made. Figure 10 below is the seismicity map for Botswana derived from the compiled catalogue which was used to identify seismic source zones.

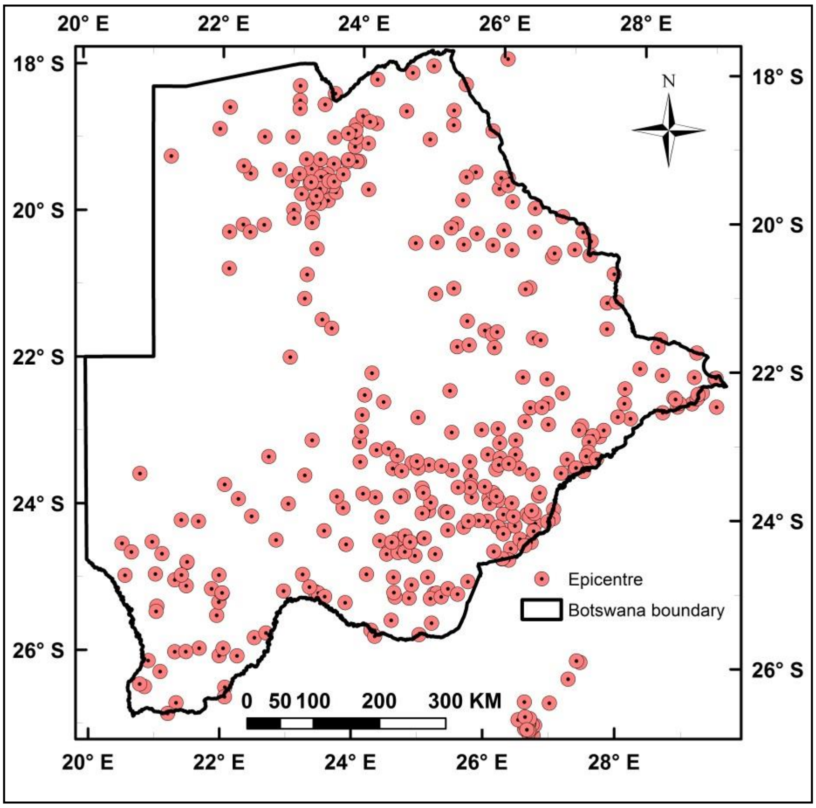


Figure 10: Seismicity map of Botswana produced from seismic data for the period 1952 to 2016.

5.2. Identification of seimsic source zones

5.2.1. Epicentre density map of whole catalogue

Point density map of the epicentres for the Botswana catalogue was made with an aim of identifying potential seismic zones based on different levels of area seismicity. Point density is a spatial analyst tool in ArcGIS which calculates the density of point features (earthquake points) around each output raster cell. Conceptually, a neighbourhood is defined around each raster cell centre, and the number of points that fall within the neighbourhood is totalled and divided by the area of the neighbourhood (ESRI, 2016). Areas which have high overlapping of the determined neighbourhood radius means they have more earthquakes occurring close to each other than others hence are areas of high seismicity. The output point density map was derived with 5 km pixel size and 30 km circular neighbourhood radius.

Based on existing literature, the magnitude 6.7 event in 1952 caused damage to structures at Maun (Reeves, 1972a) which according to Google Earth the epicentre is about 45 km away from the area. However considering the fact that this was based on the highest event reported in Botswana, a reduction of this radius by 33% to 30km could still be applicable as it would also take into account the shorter distances smaller magnitude events would affect hence the 30km radius was considered. The point density result is displayed in Figure 11 and is classified into five classes based on the number of epicentres within the 30 km radius from the middle pixel.

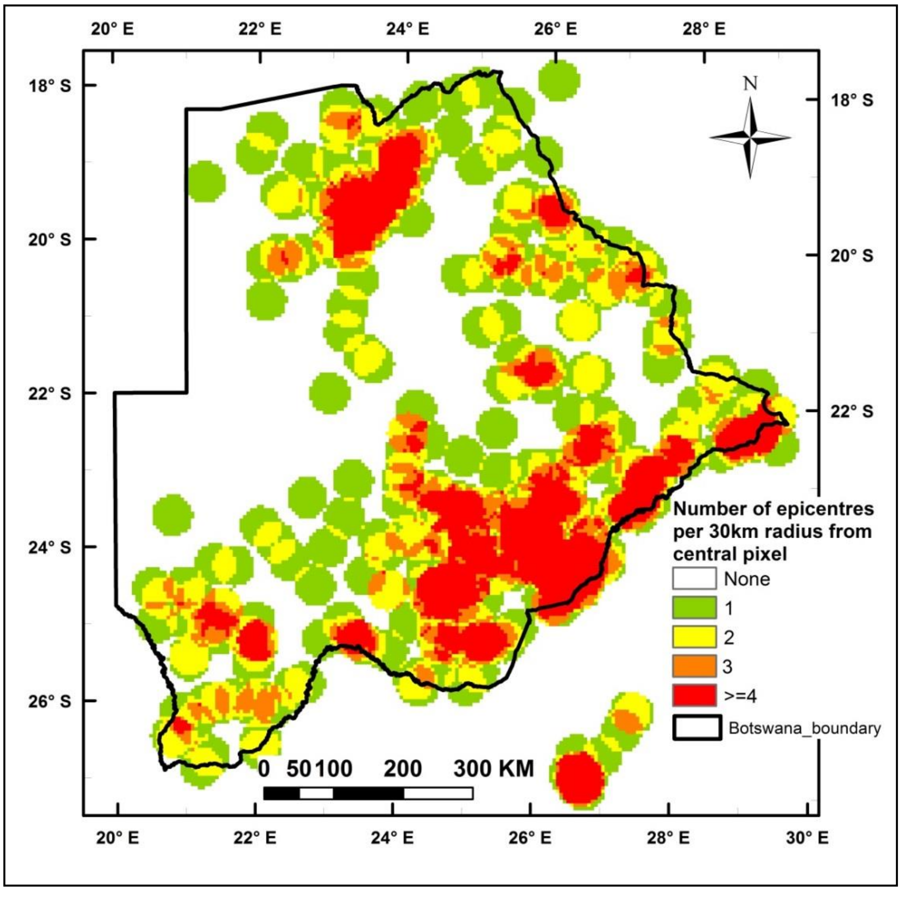


Figure 11: Shows the epicentre density result derived from the whole catalogue.

From the map, two zones comprising atleast 4 epicentres can be observed in the northwest and southern part of the country. Other relatively smaller zones can also be seen on the eastern and western parts with one zone in the southeast in South Africa. In most cases the zone with above 4 epicentres is immediately followed by thin zones of 3 epicentres some of which are clearly seen on the northwest, northeast, central and southwest. Zones with 2 epicentres and 1 epicentre respectively, follow the 3 epicentre zones. These zones can be seen in almost all parts of the country and even outside the border in northeast in Zimbabwe and in east and southeast in South Africa. However, in the west, northwest and to lesser extent central part, there is no data. This means that seismicity is relatively high in the orange and red areas.

5.2.1.1. Zonation consideration map

Contour lines were extracted from the different layers in Figure 11. Afterwards the polylines were converted into polygons and classified into two zones according to the priority to be offered as regards zonation consideration. The following procedure was formulated for consideration in seismic zonation and the result is displayed in Figure 12.

1. All zones in red comprised at least 3 epicentres within 30 km neighbourhood radius which are considered high potential for hazard resulting from frequent ground shaking. Therefore, in the zonation criteria, these red zones should be considered in the zonation process regardless of magnitude. Throughout the text, always include zones will also be referred to as MUST be zones. However, considering that the overall seismicity in Botswana is low, a MUST be in this case cannot be a MUST be in another area. t

2. On the other hand, the zones in orange which have 1 to 2 epicentres within the defined neighbourhood radius could be considered less hazard as the frequency of the events is less and therefore consideration for zonation could be done only if for example the magnitude of event is larger. These zones would also be referred to as POSSIBLE zones.

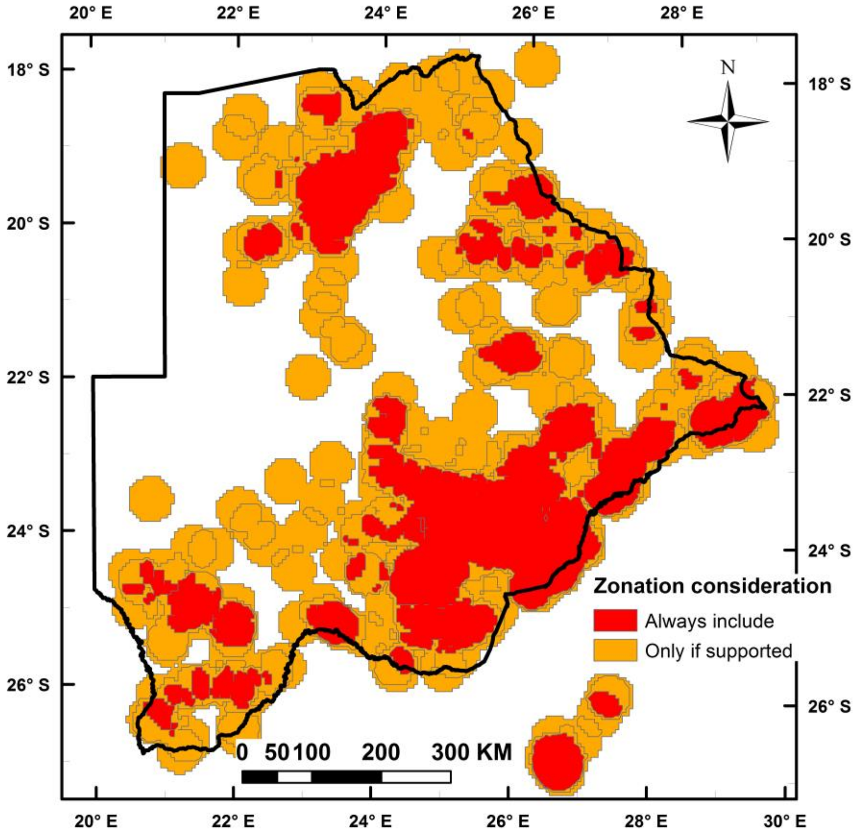


Figure 12: Map showing the results of the zonation consideration.

From the map, it can be observed that there is a large zone that must be included in the zonation on the southern part of Botswana with some smaller portions in the northeast and southwest of this major zone. Other zones that must be included in the zonation are observed in the northwest and northeast of the country and in southeastern part in the South African side. On the other hand, zones to be considered on condition basis can be observed in the northwest, northeast, central part, south and southwest of the Botswana. Two zones can also be seen in falling in Zimbabwe in the northeast and South Africa in the southeast.

5.2.2. Point density based on ML>=3.0

According to (Kusky, 2008), M = 3.0 events can be felt by people indoors. As such it would be important to consider M ≥ 3.0 to pose a certain level of hazard. In this regard an epicentre density was calculated for events of this magnitude and above and the result is displayed in Figure 13. As was the case with seismicity point density, density map for M ≥ 3.0 was calculated for 5 km output cell size and 30 km circular neighbourhood radius.

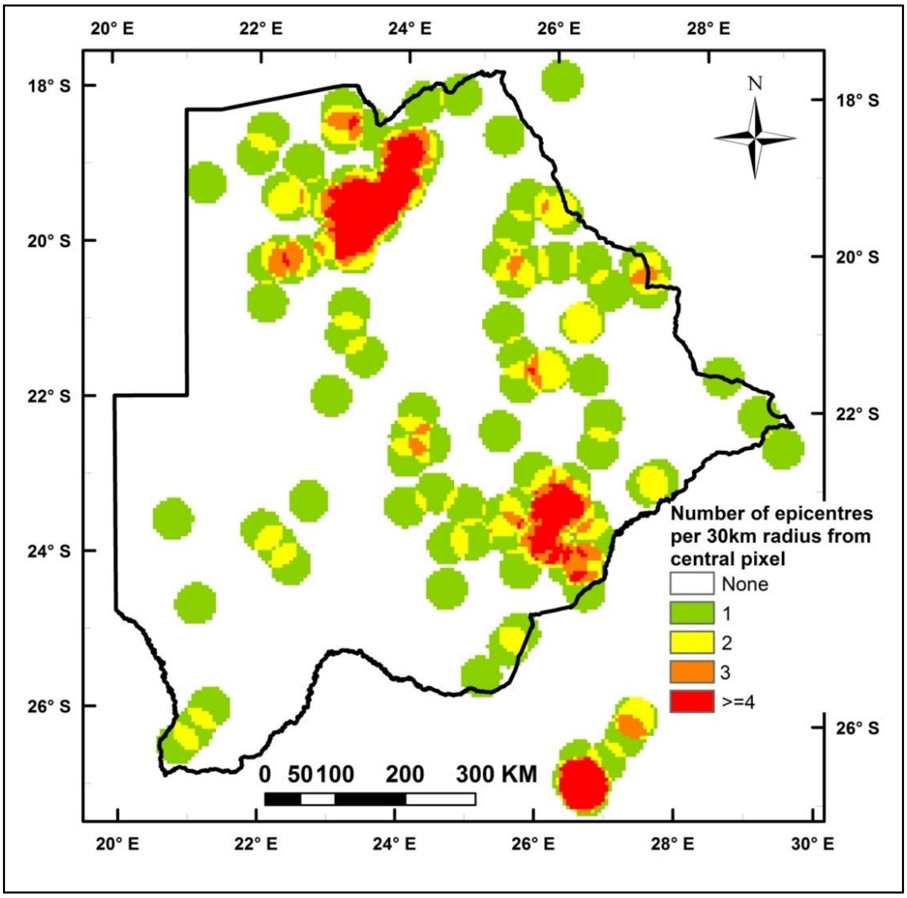


Figure 13: Shows the M ≥ 3.0 density map categorized into 5 classes. Areas with M<3 are displayed in white; those with atleast 4 epicentres M ≥ 3 are in red. Green represent areas with 1 epicentre, yellow have 2 and orange has 3 epicentres.

Generally it can be seen from the map that much of the country has 1 to 2 epicentres with M ≥ 3 within 30 km radius. However, the situation is different for three areas which show more than 3 epicentres within the defined radius. One area in the northwest of the Botswana trending NE-SW, the second one is in the southeast of the country and the last area is southeast outside Botswana border in South Africa. This means there are relatively fewer areas more than 3 epicentres with M ≥ 3 in Botswana.

5.2.2.1. Zonation consideration map

Considering that M=3.0 events can be felt indoors, numerous occurrence of these events could be a hazard mostly especially to traditional houses in rural parts of Botswana which are mainly made from combination of mud and grass (Joyce, 2016). The epicentre density map was classified into two for consideration in the zonation process (Figure 14).

1. Areas with at least 3 events could be considered hazard and therefore should be included in a zone. From the map, the red zones have 3 and more epicentres and hence fall under this category.
2. The brown zones have less than 2 epicentres hence could be considered to have low level of hazard. For the purposes of zonation, these POSSIBLE zones could only be considered for zonation only if supported by other information, for example, if an event with magnitude 4 and above is within the zone, and then it should form a zone with a neighbouring zone if isolated.

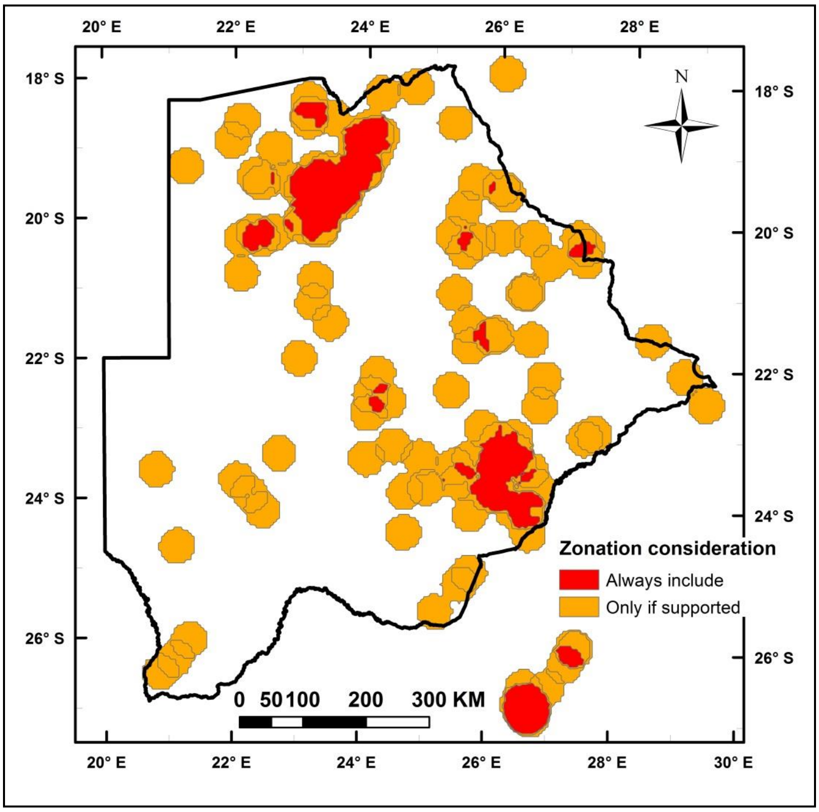


Figure 14: Shows zonation consideration map for events of at least M=3. The white colour in the map represents areas with no data.

5.2.3. Epicentre density based on ML ≥ 4.0 and zonation criteria

For every increase in magnitude by 1 unit, the associated seismic energy increases by about 32 times (USGS, 1989). Therefore magnitude 4 and 5 which are respectively 1 and 2 units step from magnitude 3 could produce more shaking energy hence must always be included in a zone. This necessitated the calculation of epicentre density for events with at least M=4 (Figure 15). The figure shows that there are fewer occurrences of M=4.0 and above events in Botswana. One area in the northwest, another in the northeast, in southeast and the last one in southeast in South Africa show to have more than 2 epicentres within 30km radius. The rest have only one event within the defined radius.

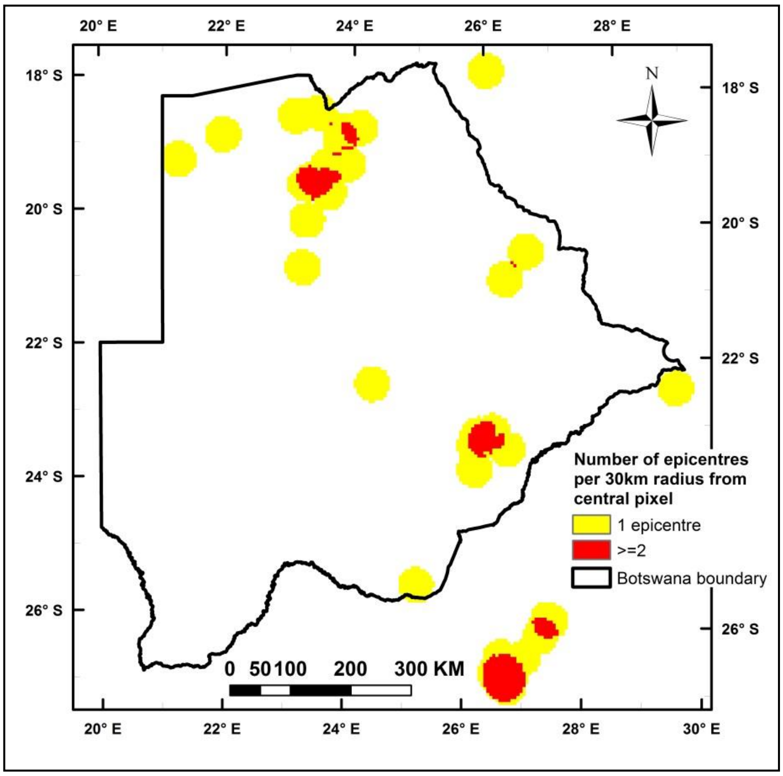


Figure 15: Shows epicentre density map for events larger than M = 4.

5.2.3.1. Zonation consideration map

Since above 4 magnitude earthquakes pose greater hazard than M=3.0, a zonation consideration map was classified in that all events above M=4.0 should be included in a zone Figure 16.

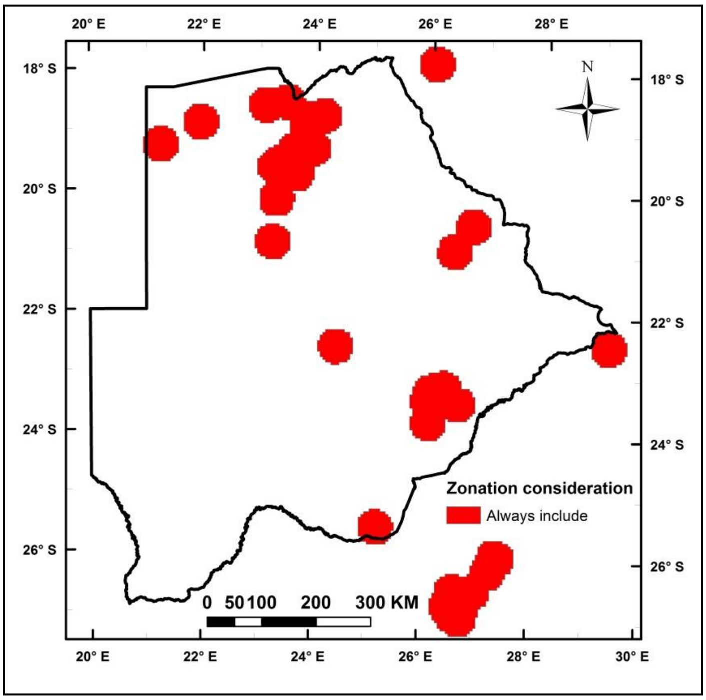


Figure 16: Shows zonation consideration map for events greater than M=4.0

5.2.4. Fault density

Based on the faults map for Botswana, a fault density map was derived (Figure 17). The fault density map was derived to help in refinement of the delineated source zones. The resulting density map was classified into 4 levels, from very low, medium, high to very high line density. Generally the result shows high line density, with some pockets of very high on the western, southern and eastern part on the country. The central and southwestern parts shows relatively medium to low values.

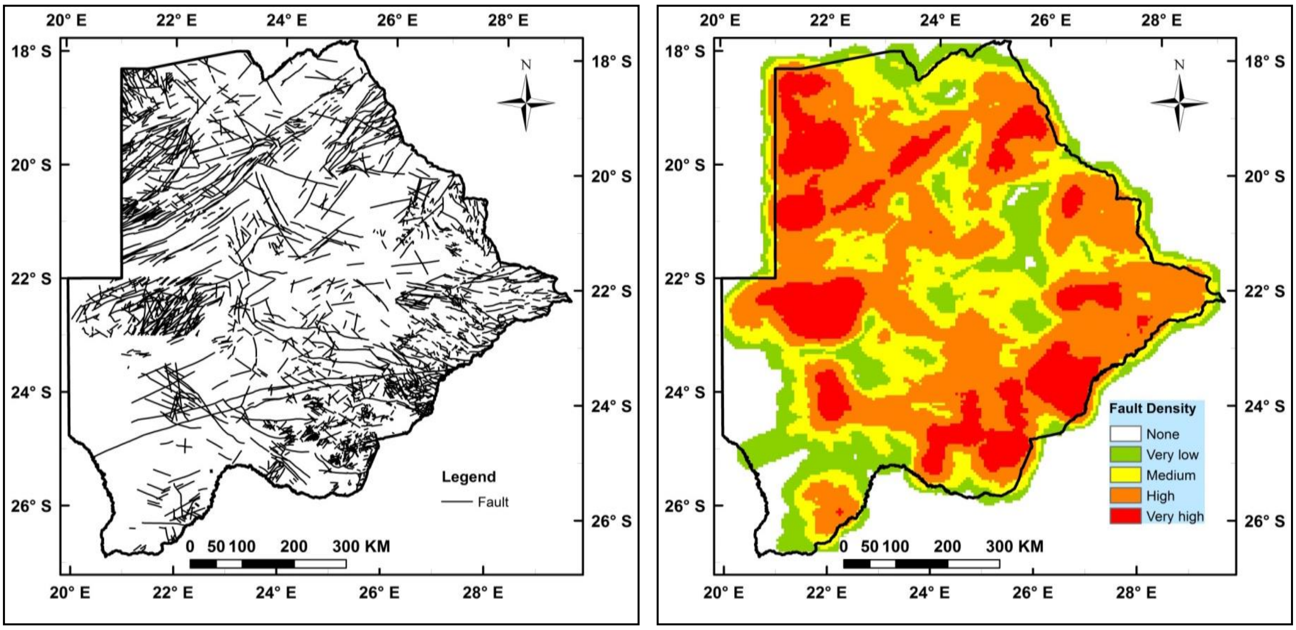


Figure 17: Map showing faults on the right and based on this a fault density map on the right was derived.

The fault map has numerous inconsistencies which renders it to have high uncertainties. For example, the map shows that there are almost no faults in the southwest part of the country in addition to numerous dense clusters faults in the south and southeast. This is highly unlikely situation on the ground. Therefore, this map will be used as a soft criterion source in relation to seismicity information.

5.2.5. Tectonic terranes

Botswana is underlain by different tectonic terraines which have formed due to different deformational processes in earth's interior. The cratons formed as a result of the collision of different cratonic blocks between 2.9 – 1.2 billion years ago (Begg et al., 2009). Examples include the Zimbabwe Craton, the Kaapvaal craton and the Angola-Congo craton. The collision process of these crustal blocks led to the formation of mobile belts which include Damara, Ghanzi-Chobe, Magondi, Limpopo mobile belts. Two basins, namely the Passarge Basin and Nosop Basin in the central and southwestern parts on the country respectively, are infilled with weakly folded strata eroded from the tectonic belts (Schlüter, 2006).

Differences in the formation processes and formation time of these terranes mean they also have different related seismicity. For example, in mobile belts the level of seismicity could relatively be higher compared to that in the cratons which is a stable crust and lowest in the basin formations. Therefore considering uniform seismicity within a tectonic terrane, Botswana could be divided into 10 seismicity zones as described in the Table 1 and the associated map in Figure 18.

Table 1: The geologic tectonic terranes available in Botswana and description for each terrane

Tectonic terrane	Description
Angola-Congo Craton	Is found to the northwest of the Damara Belt snd trends north-northwest to north. It is associated folded metasedimentary rocks which include ferruginous quartzites and weakly metamorphosed siliciclastic rocks (Key & Ayres, 2000)
Damara Belt	This belt defines a linear zone of volcano-sedimentary rocks in northern Botswana (Modie, 2000).
Ghanzi-Chobe belt	The Ghanzi-Chobe Belt was formed by extensional tectonic forces associated with a continental collision along the Namaqua-Natal Belt (Modisi, 2000). The northeast southwest trending feature borders Damara belt to the western side and the Magondi belt to the east.
Passarge Basin	In the central Botswana, between the Ghanzi-Chobe belt and Magondi belt, is overlain by thick sediments possibly belonging to the Ghanzi Group.
Magondi belt	Magondi belt is in the northeastern Botswana where it borders with the Zimbabwe craton to the south and the Ghanzi-Chobe belt to the north. This belt formed around 2.0 billion years and is associated with metamorphosed rocks (Key, 2000).
Zimbabwe Craton	Archaean age craton formed around 2.68 billion years and extend into eastern part of Botswana.
Limpopo Belt	Estimated age of 2.7-2.6 billion years (Begg et al., 2009) old, the Limpopo belt is located in the eastern part of Botswana where it formed between Kaapvaal craton to the Zimbabwe craton.
Kaapvaal Craton	This Archaean age craton extend into Botswana in the southeastern part where it is associated with rocks such as gneissic granitoids and metasedimentary & metavolcanics rocks.
Nosop	Is to the southwest of the Ghanzi-Chobe belt and is comprised of Nama Group

basin	rocks; siliciclastic sedimentary rocks (Key & Ayres, 2000).
Kheis Belt	The 2000 million years belt defines the western margin of the Kaapvaal craton (Schlüter, 2006).

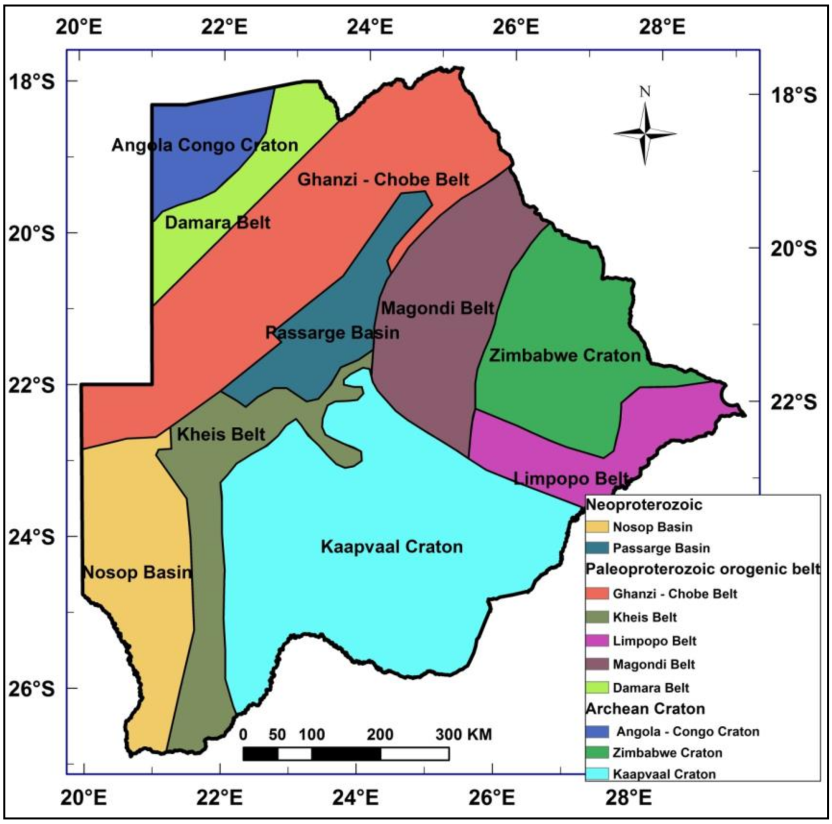


Figure 18: Tectonic terranes of Botswana (Modified from Leseane et al., (2015))

5.3. Procedure followed in the delineation of source zones

This part outlines the procedure followed in the delineation of source zones and subsequent delineation. The procedure followed two parts; one involved preparation of 3 seismicity maps and the next one was preparation of 3 magnitude maps.

5.3.1. Preparation of seismicity maps (point density)

Seismicity maps with more than 3 epicentres considered MUST include, 2 epicentres considered POSSIBLE and finally less than 2 epicentres which would NOT be considered were derived and reclassified based on scores depending on the consideration level (Table 2). Zones which are considered high in terms of hazard were given score (weight) of 1 so that they can have more influence. Next are the zones with less hazard (POSSIBLE) and were given score of 0.5 which half of the MUST zones, as its 50 – 50, they can be included or not. Lastly, the least weight of 0.2 was given to another group of POSSIBLEs which have a rare chance of being included in zonation unless they have high magnitude ($M \geq 4$) or at least 3 epicentres; which are both 1s. This was done is so that different maps should have different influence towards the final result. The 3 seismicity binary maps are displayed in Figure 19. All areas with no data have been assigned a score of 0.

Table 2: Shows the 3 seismicity maps that were derived, the seismicity criteria used in the classification, the consideration and in the last column is the score given to each map.

Map	No. of epicentres	Consideration	Score
1	≥ 3	Must	1
2	2	Possible	0.5
3	1	Possible	0.2

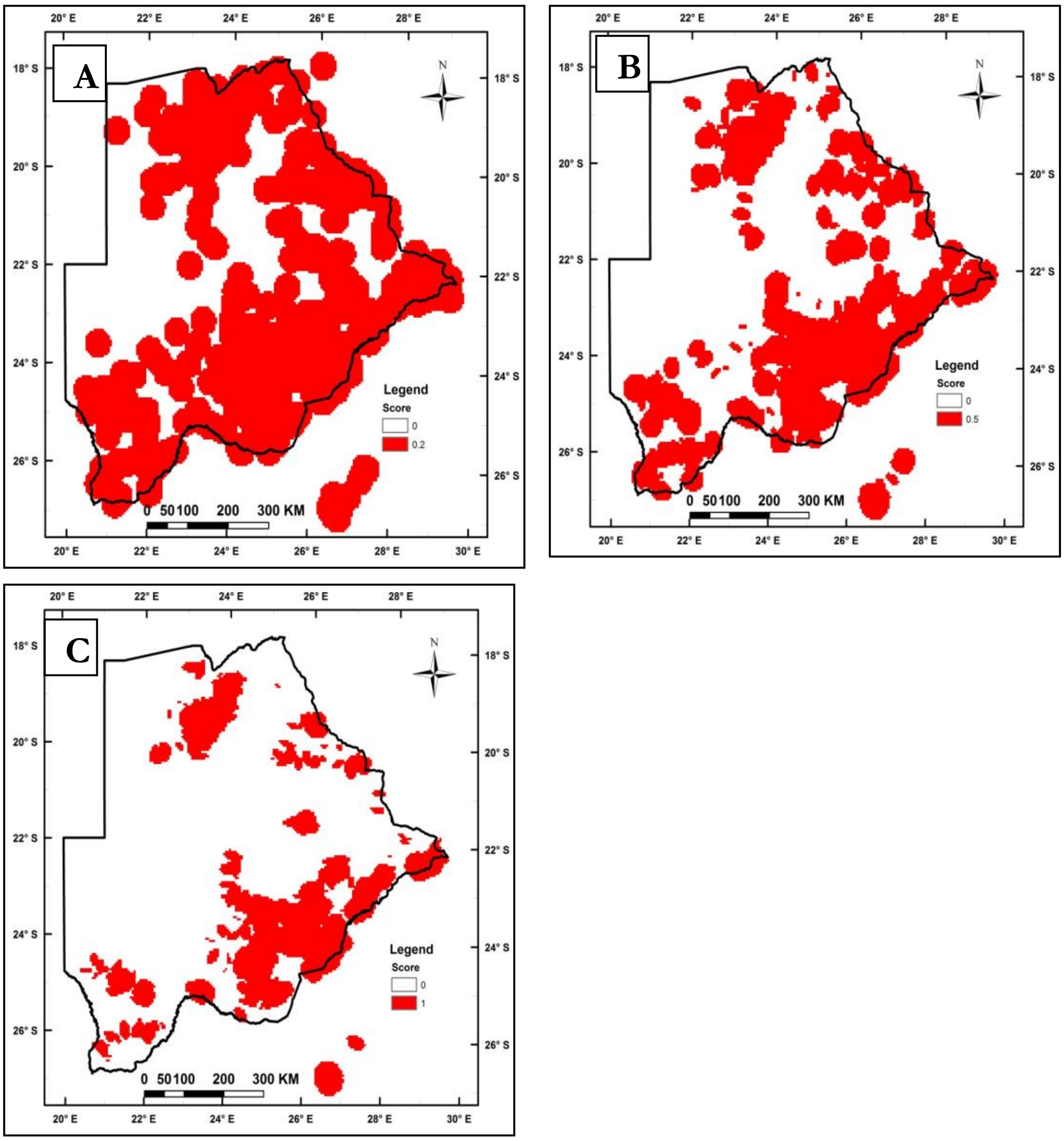


Figure 19: Shows reclassified seismicity maps with different assigned scores. Figure 1(A) is a map of 1 epicentre assigned a score of 0.2, map (B) with 2 epicentres was assigned a score of 0.5 and lastly (C) is a map with 3 epicentres and more given a score 1.

From Figure 19 above, (A) shows that besides some central and western parts, the rest of the country is seismic, even if of low seismicity. Further there are also epicentres 200 km outside Botswana border in northeast part in Zimbabwe and east and southeast in South Africa. (B) shows that the areas with no data (assigned a score of 0) are more in the western and north-eastern parts of the Botswana with one zone in southeaster part in South Africa. Lastly, (C) shows that even fewer areas have above three epicentres within 30km radius, much of which are in the northwest, northeast, southern and southwest of the Botswana. Two smaller clusters with more than 3 epicentres can also be seen in the southeast in South Africa. Generally it can be seen that the most seismically active zones are the Okavango are in the north and the south-central part, near the border with South Africa.

5.3.1.1. Magnitude maps

Magnitude, M ≥ 4 considered as MUST include, M ≥ 3 but less than M=4 considered as POSSIBLE and finally less than 3 magnitude NOT considered were reclassified and respectively assigned scores 0.2, 0.5 and 1. The whole method is summarized in the Table 3 below and the resultant maps are displayed as Figure 20**Error! Reference source not found.**.

Table 3: Shows the 3 maps that were derived based on magnitude, the assigned consideration which determined the score to be awarded.

Map	Magnitude	Consideration	Score
1	≥ 4	Must	1
2	≥ 3 < 4	Possible	0.5
3	< 3	Possible	0.2

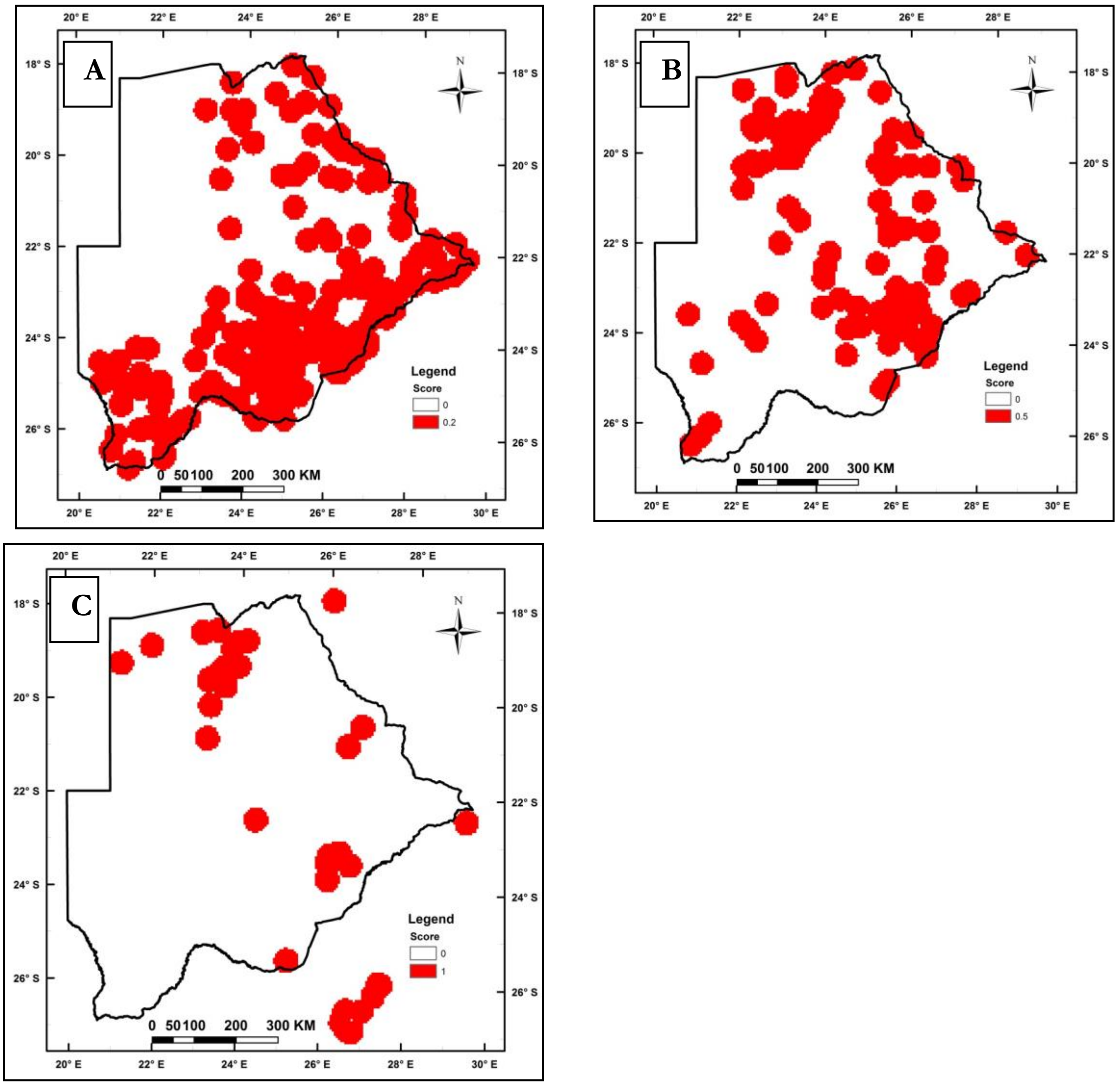


Figure 20: Shows reclassified magnitude maps with different assigned scores. (A) is a map of M < 3 assigned a score of 0.2 while the no data was assigned 0, (B) is M = 3 map assigned a score of 0.5 (no data assigned 0) and lastly (C) is map of M>=4 assigned a score

The result in Figure 20 shows that much of Botswana has more events with M > 3 as evident from (A). The spatial distribution of these events is not uniform they are mostly concentrated in southern and north eastern sides. Much of the western part has no data hence have a score of 0. From (B), even fewer areas with M=3 events in Botswana most of which are concentrated in the eastern, northeast and northwest parts. This map has relatively more areas with no data which were assigned a score of 0. Lastly (C) shows that Botswana has very few areas with M>=4 which were assigned a score of 1. Apart from inside Botswana, three areas can also be seen in the northeast in Zimbabwe and in the east and southeast in South Africa.

The 6 derived maps with their respective scores were then summed up and Figure 21. The Figure shows that very few areas satisfied all the conditions which are provided in red and have a total score of 3.4. Areas with this highest score are in the northwest, northeast and southeast in Botswana and also southeast in South Africa. Areas with no data have a score of 0.

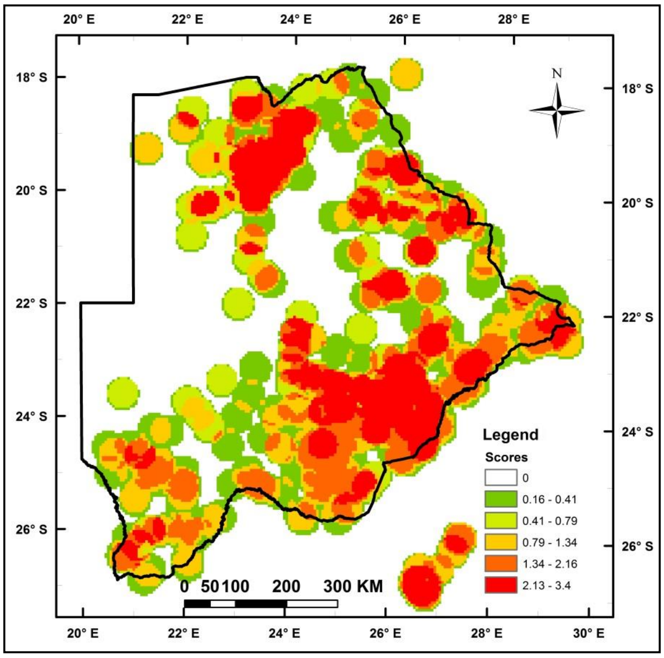


Figure 21: Shows the sum of the 6 maps assigned different scores. Areas which met all the conditions have a total score of 3.4 while those with no data have 0.

A condition was applied to the result derived in Figure 21 to isolate areas with score value >=1 and the result is reclassified as a binary map in and is displayed in Figure 22. This means that for the pixels displayed in the figure have fulfilled the following 7 conditions:

1. Have at least 3 epicentres of any magnitude
2. Have at least 1 epicentre of $M \geq 4$
3. Have at least 2 epicentres of $M \geq 3$

Generally, the result above shows a bigger zone with a score above 1 in the southeast of the country. Apart from this zone, many others can be seen scattered in the east, northeast, North West and southwest in Botswana. One zone in northeast in Zimbabwe also shows total pixel value greater than 1 as is another in the southeast in South Africa. The result from this map therefore show areas which were considered for the delineation of seismic zones discussed in detail in the following sections.

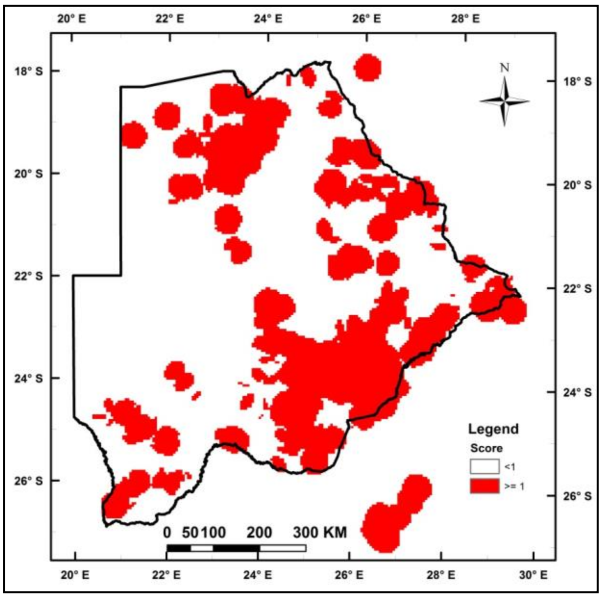


Figure 22: Shows pixels which have value >=1 in red and those with total scores <1, have been displayed in white colour.

5.3.1.2. Delineation of source zones based on geology

This section provides explanations on how the source zones were delineated based on the binary map in Figure 22. The contours were extracted from the binary map, which were then converted to polygon from polyline. The converted polygons were then clipped based on the tectonic terrane map of Botswana (Figure 23).

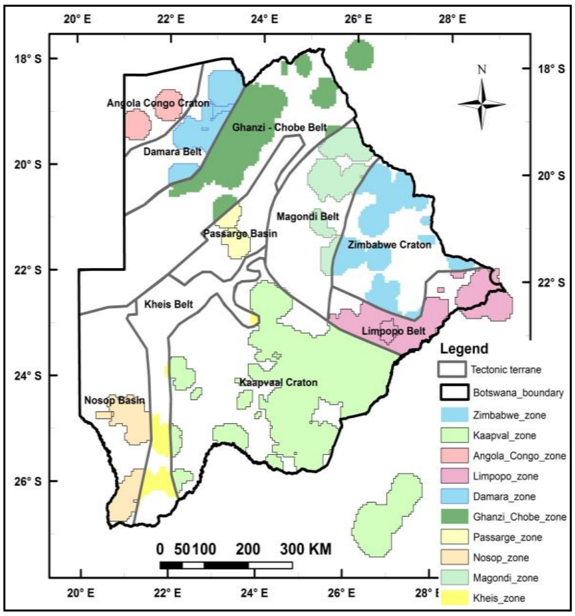


Figure 23: Shows the zones confined within each tectonic terrane. The polygon zones have been displayed in similar colours within the same terrane (A). In (B) zones falling outside Botswana border which clipped in (A) have been displayed.

5.3.1.3. Delineation of zonations based on MUST and POSSIBLE maps

The process of delineation of final zones took into consideration seismicity (and also magnitude) distribution in the zone, the MUST vs POSSIBLE polygons (score >=1 and score >=2) and finally tectonic terrane. Below is a map with seismicity overlay on tectonic terranes (Figure 24**a**), an overlay of polygons for scores>=2 on scores >=1 (Figure 24**b**) and finally delineated zones overlay on MUST vs POSSIBLE map (Figure 24**c**). In total 16 zonations were made and the description is provided below the figure.

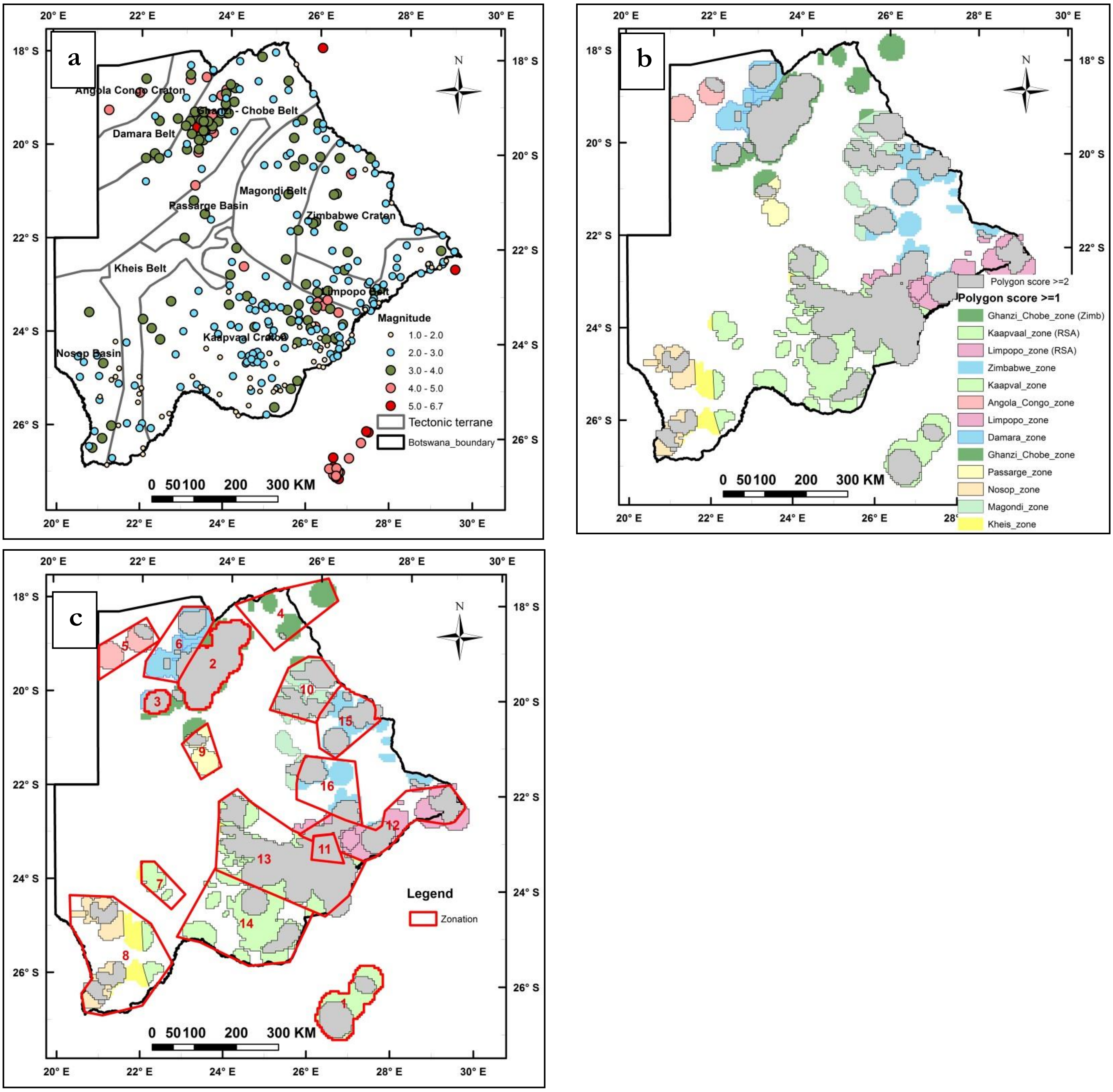


Figure 24: Map (**a**) shows epicentres overlay on 10 tectonic terranes present in Botswana. An overlay of score >=2 polygons on score >=1 polygons in map (**b**) helped in discriminating areas with high scores from the low. (**c**) is the map showing delineated zones

The zone is located in the southeast of Botswana in South Africa. Despite showing 2 different zones from the score>=2 (light green polygon), for score>=1 (brown polygon) it shows single continuos zone. In terms of seismicity, the area shows high magnitude (M >= 5) events only. Therefore due to high magnitude earthquakes this area have been defined into a single zone based on the polygon boundary from score>=1.

Zones 2
Is a highly seismicity zone in the NW Botswana in the Ghanzi-Chobe mobile belt. The area has been selected because it comprise cluster os high magnitude earthquakes. Based on the polygon from scores >= 1 (in green color) the zone has a smaller elongation to the southeast, however the brown polygon (for score >= 2) suggest otherwise. The bigger zone shows high seismicity with relatively M > 3 and the lower part has only 4 isolated epicentres. Therefore the upper polygon was considered zone based on the brown polygon boundary.

Zones 3
The smaller zone left after selection of Zone 2 in the southwest is Zone 3. From the score >=2 consideration, the zone is the same which is also supported by relatively M = 3 events localised in the zone although tectonic terrane suggesting that these are separate zones. But stronger facts support that this is a single zone. Therefore zonation was based on the polygon from the >=2 score.

Zones 4
Is located NE of zone 2 in the Ghanzi-Chobe mobile belt. The zone generally shows smaller polygons for score >= 1, based on which the zone was digitized as single zone. Delineation was done to include 3 epicetres with or magnitude range M=2 -3 (all within Botswana) because they are contributing to the green polygons. On the northeast, the zone extend into Zimbabwe to incorporate one M=5 event.

Zones 5
Is located northwest of Botswana in the Angola-Congo craton. Polygon for score >=1 shows two zones while that of score >= 2 suggest the presence of only one zone. There are only 3 epicentres in the terrane two of which are of M=4 while one is of lower magnitude. Therefore based on relatively large and isolated event localised in this terrane, this zone was delineated.

Zones 6
This zone located NW of Botswana in the Damara mobile belt shows broadly scattered epicentres. For score >=1 this is single zone but score >=2 suggest otherwise. However, seismicity suggest more events with higher magnitude M=3 and M=4. Therefore supported by score >=1 and seismicity this has been delineated into a single zone.

Zones 7
The zone is located in Kaapvaal craton within Botswana. The are comprise two disjoined zones for score >=1 with linearly distributed epicentres which generally M =3. These two points strongly suggest this is a zone hence was digitized.

Zones 8
The zone in the southwest of Botswana spread across three tectonic terranes namely; Nosop basin to the left, Kheis belt in the centre and to the right is Kaapvaal craton. Based on score >= 1and that of >=2,

these are 2 separate zones. One on top with another below it with relatively no data zone in between. However seimicity suggest otherwise, the entire area comprise relatively smaller events M=1 and 2 with four epicentres with M=3. Therefore based on seismicity, this zone was digitized as single zone.

Zones 9

Is in the Passarge basin. Both score >=2 and >=1 shows one zone only divided tectonic terrane. These two scores strongly suggest that these events belong in the same zone and that the M=4 event on the tectonic terrane boundary may have just been mislocated or attributed to the uncertainties in the tectonic terrane boundary. Therefore it was included into Zone 9 together with 3 other epicentres.

Zones 10

Is in the magondi belt. there is agreement on this zone based on scores (right green) >=1 and score >=2 (in brown), although the latter suggests presence of 2 zones not one. However overall seismicity show that the area comprise events of magnite in the range M=2 - 4. Therefore base on seismicity and score >=1, this zone was digitized.

Zones 11

This zone cuts across two tectonic terrane namely; Kaapvaal craton and Limpopo belt. The zone has score>=2 and has cluster of relatively bigger events to its surroundings which strongly suggest its a separate zone of high magnitude events. Therefore based on high magnitude earthquakes this was delineated as a zone.

Zones 12

Is in the Limpopo mobile belt. it shows generally score >= 1 with some patches of score >=2. Seismicity shows that the area has relatively smaller M=2 events and therefore it was delineated into Zone 12. The zone was extended to include M=5 event located near Botswana border in South Africa.

Zones 13

Is a larger zone in the Kaapvaal craton which shows both score >=1 and >=2. However, it has been delineated because it shows a linear seismicity pattern from SE to NW which suggests it is a zone. To the north of the zone, two M=2 events were included despite that they are located in the no data zone because this magnitude is prevalent in the zone.

Zones 14

The zone in the Kaapvaal craton shows relatively similar results for score>=1 while score >= 2 shows two zone. Seismicity shows relatively smaller events compared to the Zone 13 above it. Hence this was delineated as Zone 14 based on seismicity and score >=1.

Zones 15

Zone 15 is located in the northen part of the Zimbabwe craton. The zone shows similar score >=1 and 2. The zone shows more events with M=2 and M=3 with one of M=4. The zone was delineated based on scores >=2.

Zones 16

Zone 16 is like Zone 15 is also located in the Zimbwabwe craton but to the southwest of the latter. The zone shows polygon of score>=1 and 2. In terms of seismicty, the zone shows general M=3 which could be import for consideration in hazard considering that considering that the country has relatively smaller events. Therefore the zone was digitized to include only the zone in Zimbabwe craton which shows more M=3 events.

5.3.1.4. Delineation of final zonations

Figure 25 below is the map with the final source zones which were used in the hazard analysis. The total number of zones is 15 reduced from initial 16. This is because Zones 10 and 15 in the northeast of Botswana were merged based on the fact that they display similar seismicity. Zone 11 which was initially smaller was also extended to incorporate relatively larger events in the western part and also smaller ones in the eastern part which are also common in the zone.

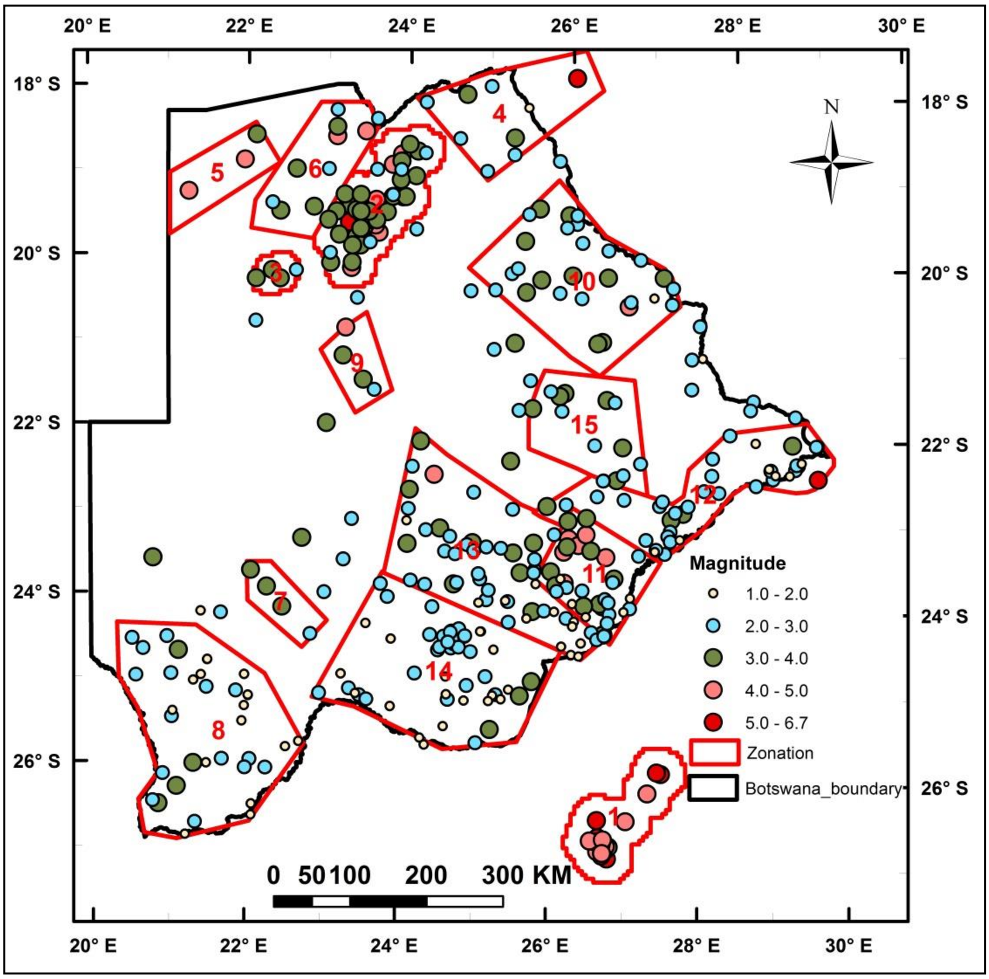


Figure 25: Map showing 15 final zones overlay with earthquake epicentres

5.4. Seismic hazard analysis

5.4.1. Seismic reccurence relations

For each seismic source zone, parameters reflecting their characteristics were computed following equation (1). These parameters include: the a- and b-values, activity rate (λ), the lower bound magnitude for catalogue completeness (Mlow), the expected maximum magnitude (Mupp), the earthquake depth, and the suitable regional attenuation relationship for the strong ground motion.

Calculation of the a and b-values was done using the log-linear least square reggression analysis of the seismic data using the equation (1). The a- and b-values indicates the seismic activity of the area, where b-value indicates the proportion of small to large magnitude earthquakes. Naturally b-values falls within 0.5 and 1.5 depending on the tectonics of the area (Mandal, 2013). In this study, the b-values were computed for all the earthquakes in the catalogue because the catalogue is not complete for any specific magnitude. The **β**-values were derived from determined b-values, the activity rate (**λ**.) was derived by dividing the number of events by years. The reccurence relationships parameters which were used in the the hazard computation in CRISIS2015 for each seismic zone are displayed in Table 4 and the reccurrence plots, which used 0.2 magnitude step, are provided in **Appendix B.** The expected maximum magnitude (Mupp) is selected based on the observed maximum magnitude in each zone and so was the lower bound magnitude (Mlow).

Table 4: Shows that parameters used in the hazard analysis in CRISIS2015. a and b are the Gutenburg Richter parameters; Mlow = lower bound magnitude; Mupp = expected maximum magnitude; λ is the activity rate which is the number of events over a certain time period; β = b*ln(10).

Seismic Zone	**Number of events**	**a**	**b**	**Mlow**	**Mupp**	**λ**	**β**	**Depth (km)**
1	197	3.91	0.41	3.8	5.4	4.58	0.95	10
2	42	3.33	0.58	2.5	6.7	0.66	1.33	17
3	4	3.62	0.99	3	3.6	0.36	2.28	10
4	9	1.88	0.43	2.0	5.2	0.19	1.0	18
5	3	3.82	0.88	3.9	4.5	0.23	2.03	8
6	9	3.16	0.71	2.8	4.5	1.65	0.33	10
7	4	5.48	1.51	3.2	3.7	0.15	3.47	14
8	35	3.04	0.82	1.1	3.6	1.06	1.89	7
9	4	1.21	0.25	2.4	4.8	0.67	0.59	47
10	28	4.52	1.12	1.9	4.1	0.61	2.57	7
11	33	3.32	0.64	1.6	4.6	0.67	1.48	20
12	41	3.63	0.95	1.3	5.2	1.0	2.18	15
13	55	4.17	1.02	1.5	4.1	1.1	2.36	10
14	52	3.60	0.99	1.6	4.0	1.21	2.28	11
15	12	4.15	1.14	2.1	3.8	0.27	2.63	8

In the calculation of the b-value for Zone 1, the number of events that were considered was increased to 197 from an initial 23. Initially, the consideration was for M ≥ 5.0 events outside Botswana. However, this could have an effect on the trendline when plotting to get the b-values.

Focal depth for each source zone was determined based on the average depth of 3 largest recorded events in the zone (Grunthal, 1999), and where zero depth is recorded, then 10 km fixed depth was adopted (USGS, 2016a).

5.4.2. Attenuation model

There are several attenuation models prepared for different tectonic regions in the world, for example active shallow crust, stable continents and subduction zones. Attenuation models describe the loss of energy with every cycle of the seismic wave. That leads to decreased amplitudes with distance and time, but frequency dependent. As there is no existing attenuation model specifically for Botswana, this study used the Ground Motion Prediction Equation by Atkinson & Boore (2006). The choice this model was based on the fact that eastern North America which includes Canada displays similar Precambrian geology to that found in Botswana.

5.4.3. Seismic hazard

The hazard analysis for Boswana was computed for 15 delineated seismic zones, using CRISIS2015 software developed by (Ordaz et al., 2015). Using the sofytware, hazard computation was performed based on the grid nodes system of 50 longitude lines from 19.8^0 E with 0.2^0 (approximately 20 km) increment, and 55 latitude lines from 28.4^0 E with the same 20 km increment.

The hazard map for Botswana was derived based on the standard return period considered worldwide which is 475, corresponding to a 10% probability of exceedance of a certain magnitude, for a 50 year lifetime.

5.4.4. Hazard results

Hazard map was calculated for a 475 year return period which is the most significant and the result is displayed in Figure 26 and for 0.2 vibration period which was adopted from the (USGS, 2016b).

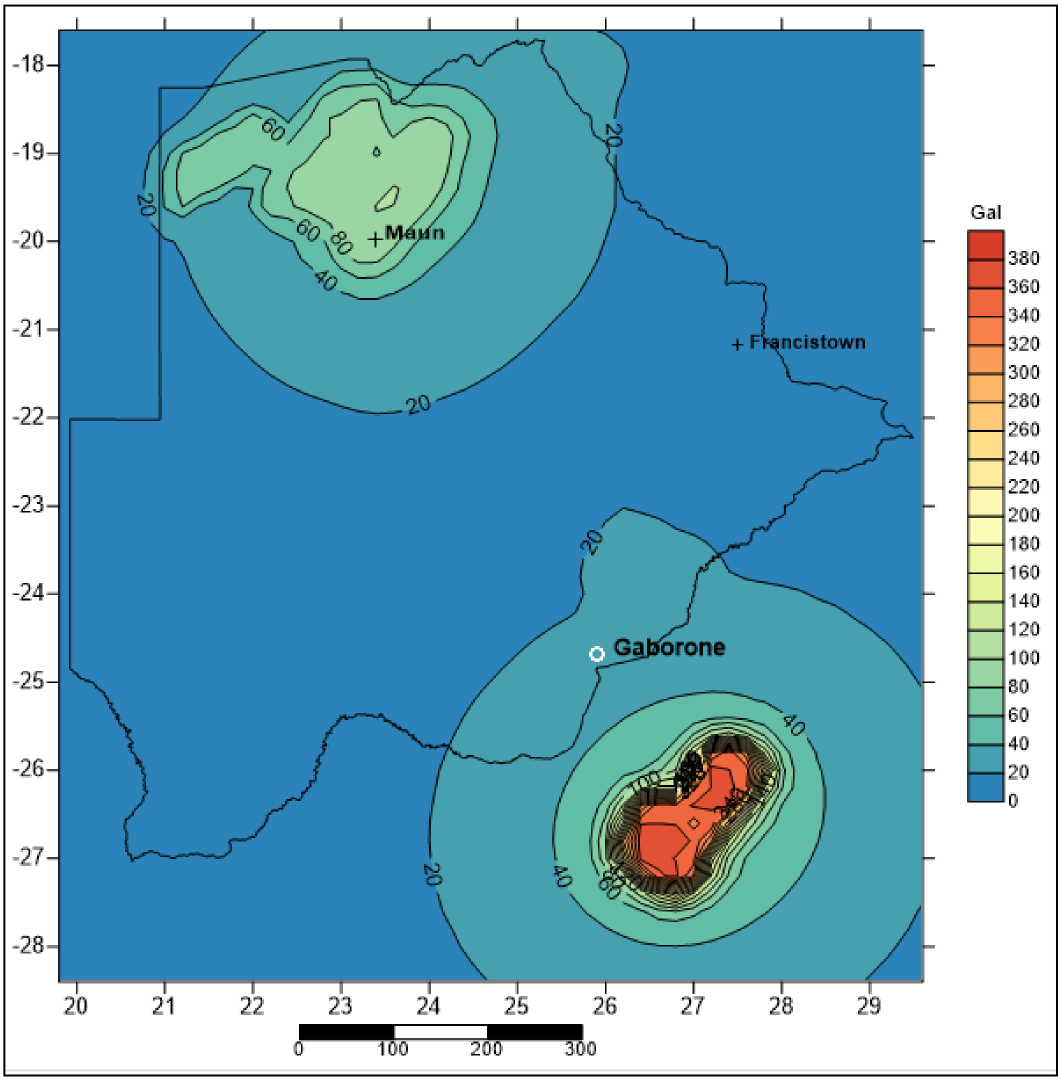


Figure 26: PGA seismic hazard map of Botswana for the return period of 475 years. The map presents 0.2 vibration period with a 10% probability of exceedance in 50 years. The contour interval used is 20 gals.

As expected, the result shows that almost all of Botswana which has relatively low seismicty have low level of hazard between 0 and 20 gals, except for Maun in the northwest which shows a hazard level of 80 gals. On the other hand, an area in southeast Botswana in South Africa shows maximum PGA of 320 gals. However, it was noted that few sources looked to contribute to the hazard analysis, which are three zones in the northwest and one in southeast Botswana and southeast in South Africa. The rest are quiet. The results a bit different with those in Figure 27 There could be a problem with settings in the software used, unfortunately, this research could investigate more due to time constraint hence recommends that furture work could look into it.

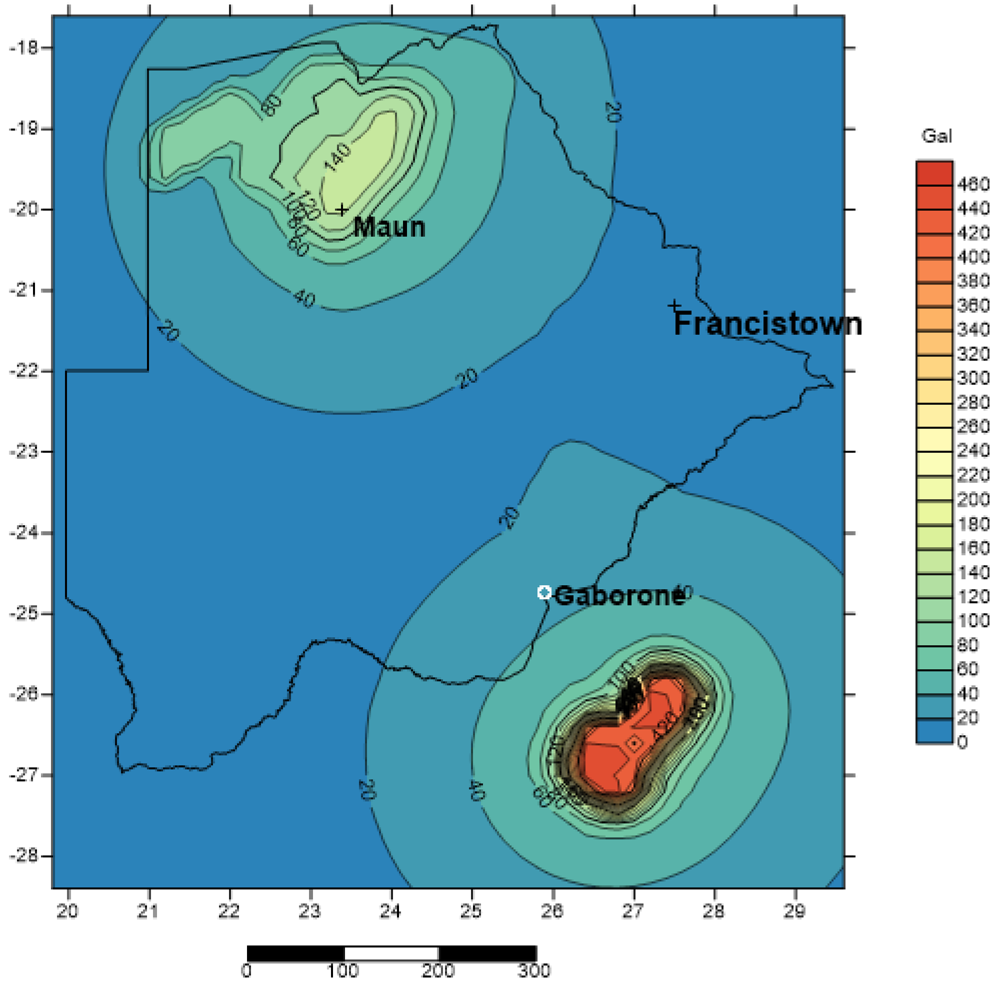


Figure 27: PGA seismic hazard map of Botswana for the return period of 976 years. The map presents 0.2 vibration period with a 5% probability of exceedance in 50 years. The contour interval used is 20 gals.

Comparison was made with results obtained from the regional study by Midzi et al., (1999) and there is some agreement. Maun area als shows 40 gals although in this research there is no zone east of Botswana as is the case from the regional study.

6. CONCLUSION AND RECOMMENDATION

This research analysed instrumental seismic data acquired from a network of 21 seismic stations in Botswana to locate earthquakes for the purpose of updating the local earthquake catalogue for hazard analysis. Using python programming language, codes were established and 2 events were identified and located in HYPOELLIPSE software. However, it was observed that programming posed a lot of challenges.

Seismic data from various sources was acquired and compiled into catalogue for Botswana. 381 seismic records were compiled from online bulletins by the Council for Geosciences, the International Seismological Centre, and the United States Geological Survey. The data was for the period from 1952 to 2016 and was reported in various magnitude types hence magnitude homogenisation to one magnitude type was necessary. Considering that 52% of the events in the catalogue were reported in local magnitude (ML), the magnitude type was adopted for use and all other magnitude types were converted to ML based on different established relations. However, the number of events used in this analysis could was less considering that considered many studies who use data covering 100 years.

A plot of magnitude frequency versus time was done for the compiled catalogue. From visual interpretation, the catalogue was incomplete and therefore no minimum magnitude was determined for use in hazard analysis.

Using seismicity (density), magnitude, fault and tectonic terrane data, this research successfully identified and delineated 15 seismic source zones. Different scores were given to these different data sets depending on their importance. The weightage maps were summed up and conditions to isolate pixels with score $\geq$ 1, and $\geq$ 2 was given. 15 seismic source zones were identified and delineated and were used in the hazard analysis. Tectonic terrane and faults data were used to refine the delineated source zones before coming up with the final zones.

Hazard analysis was performed based on the 15 delineated source zones. The hazard result for 10% probability of exceedance in 50 years shows hazard level of 80 gals for Maun area and a generally a range of 0 to 20 gals for much of the country. Gaborone shows 20 gals and an area to the south of it shows a maximum PGA of 320 gals. This result correlates very well with the regional study. CRISIS allows hazard computation and result visualization, however, it is not friendly as far as data integration is concerned. This therefore posed a huge challenge in presentation of the hazard results, for example, when the national boundary is overlaid on the hazard result, all seismic zones outside the boundary are clipped. Further, the program does not allow naming of cities and towns to be displayed hence it was done using other programs. However, this challenge was overcome by using Golden Surfer software.

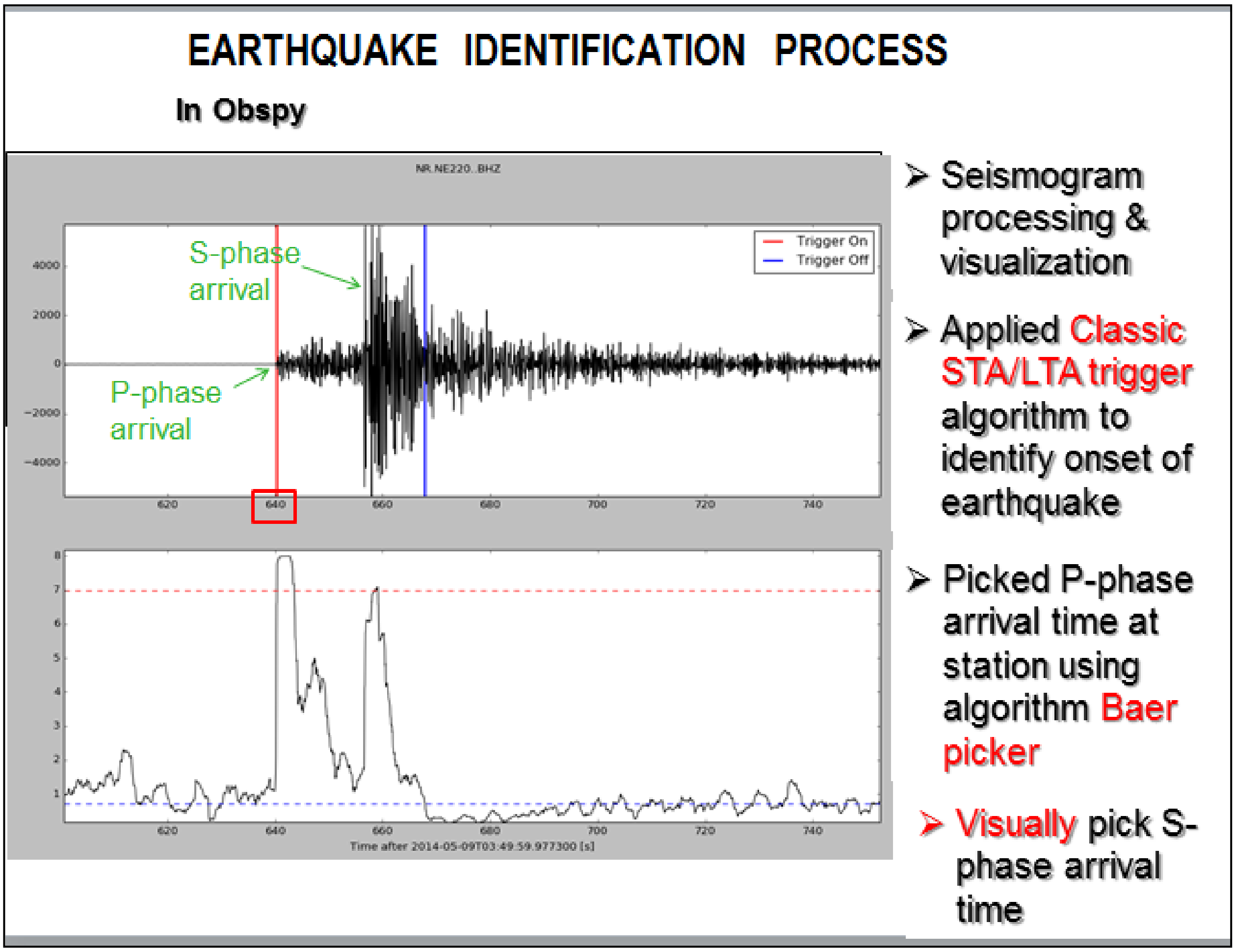
6.1. Recommendation

The following recommendations are made in this research:

1. Further processing of instrumental seismic data from the Botswana network would help in updating the catalogue which could effectively provide good hazard assessment.
2. The methodology for identification and delineation of seismic source zones could be improved by incorporating digital elevation model

Appendix A: Provide code established for identifying earthquakes from instrumental seismic data and the

```
from obspy import read
from obspy.io.xseed import Parser
from obspy.core import UTCDateTime
import numpy as np
from obspy.signal.trigger import classic_sta_lta
from obspy.signal.trigger import plot_trigger
from obspy.signal.trigger import pk_baer
import matplotlib.pyplot as plt

st = ("//GEOZ/Users/Area1B/Documents/MSC_Data/Month/NR.NE220/NR.NE220.BH_.2014.05.mseed"
dataless = Parser("//GEOZ/Users/Area1B/Documents/MSC_Data/dataless/NE220.sed")
t1 = UTCDateTime(2014,5,9,3,50)
t2 = UTCDateTime(2014,5,9,4,10)
st = read(st, format="MSEED", starttime=t1, endtime=t2)
st.plot()
st = st.select(channel = "BHZ")
st.detrend('linear')
st.detrend('demean')
st.filter("bandpass", freqmin=1, freqmax=5, corners=2, zerophase=True)
tr = st[0]
tr.plot()
#%%
df = tr.stats.sampling_rate
cft = classic_sta_lta(tr.data, int(2.5 * df), (20 * df))
plot_trigger(tr, cft, 5.0, 0.7)

#%%
df = tr.stats.sampling_rate
data = tr.data
p_pick, phase_info = pk_baer(tr.data, df, 20, 60, 7.0, 12.0, 100, 100)
arrivaltime = t1 + (p_pick/df)
print (p_pick)
print (phase_info)
print (p_pick/df)
print arrivaltime
```



HYPOELLIPSE Input files and Output file containing location and focal mechanism plots for the 2014 Orkney earthquake in South Africa using the HYPOELLIPSE software

1. **Station data**

```
n0124s30.92 023e55.97  980
 n01*     18
 n0224s6.811 021e46.94 1153
 n02*     18
 n0322s59.58 020e11.73 1313
 n03*     18
 n1325s28.53 022e51.44 1030
 n13*     18
 n2023s21.78 025e51.58 1020
 n20*     18
 n2125s48.71 024e48.05 1158
 n21*     18
 END
```

2. **Phase data**

```
n01 ezd1 140805102329.30        85.60
n02 ezd3 140805102353.50        141.8
n13 ezd0 140805102333.50        92.40
n20 iz 0 140805102331.80        87.80
n03 iz 4 140805102417.20        153.1
n21 ez 0 14080510239.800        39.50
n02  n   140805102353.50        140.8
C*       YrMoDyHrMn P-Sec       S-Sec
```

3. **Calibration data**

```
n03 D 140805 150805
n20 D 140805 150805
n13 D 140805 150805
n02 D 140805 150805
n01 D 140805 150805
n21 D 140805 150805
```

4. **Crustal model**

```
! Model 1: Average velocity model for southern Africa
! This is an example of a linear increase over a halfspace.
VELOC              5.80       00.00     1.68
VELOC              6.50       20.00     1.71
VELOC              8.04       38.00     1.73
VELOC              8.05       60.00     1.73
```

5. **Headopt.prm file**

```
! begin headopts.prm

blank source            D

header content           ITC Botswana network processing parameters


calibration        6
-407-374-347-304-260-235-207-171-142-114 -88 -65 -43 -20
0.198.391.574.725.848
.943 102 111 119 129 138 146 154 162 168 169 167 154 139 109.856.555.234
-34 -66
-113 -90 -73 -40  -6.084.267.529.719.904 106 119 132 145 156 168 180 191
200 208
 214 220 226 234 242 252 259 269 278 286 294 302 303 306 295 288 266 234
168 125
-113 -90 -73 -40  -6.084.267.529.719.904 106 119 132 145 156 168 180 191
200 208
 214 219 226 233 242 251 258 267 275 283 289 295 294 295 283 280 269 257
220 208
```

```
-244-222-204-171-137-123-104 -78 -59 -41 -25 -
12.012.141.251.368.484.599.692.768
.828.886.950 103 111 120 128 137 146 155 163 171 172 175 164 156 135
103.371  -6
 -95 -72 -55 -22.123.267.450.713.903 109 125 138 151 164 175 186 198 209
219 226
 232 238 244 252 260 269 276 285 294 301 307 313 312 313 302 298 288 276
238 226
   0   0   0   0   0   0   0   0   0   0   0.288.432.561.680.786.891.983
107 114
 121 128 136 144 154 163 173 182 192 201 209 215 210 188 155 117.771   0
0   0

! test variables   #   default    definition
!     test          1    1.7800    ratio of p-wave velocity to s-wave
velocity.
!     test          2    5.0000    lt 0 no elev cor/ =0 use 1st vel/
!                                  gt 0 use this.  use only if
test(8)=0.
reset test          2   -1.
!     test          3    0.0000    first trial latitude in degrees,
unless zero.
!     test          4    0.0000    first trial longitude in degrees,
unless zero
!     test          5   -99.000    first trial depth in kilometers,
unless = -99.
reset test          5   30.
!     test          6   0.0000     radius for aux rms values. if neg
cont
!                                  iteration at most neg point.
!     test          7   4.0000    minimum number first motions required
to plot
reset test          7   -100.
!     test          8   0.0        elevation of top of layered velocity
models
reset test          8   3.0
!     test          9   0.0        if 0.0 set neg depths to -00
reset test          9   1.0
!Distance Weighting
!     test         10   50.0000    begin distance weighting on this
iteration.
reset test         10    5.0
!     test         11   50.0000    xnear = greatest distance with weight
of 1.0
reset test         11  100.
!     test         12  100.0000    xfar = least distnace with weight of
0.0
!                                  see test(46) also.
reset test         12  150.
!Azimuthal Weighting
!     test         13   50.0000    begin azimuthal weighting on this
iteration.
!Truncation Weighting
!     test         14   50.0000    begin weighting out large resids on
this iter
!     test         15   10.0000    give zero weight to residuals gt
this.
```

```
reset test        15    5.0
!Boxcar Weighting
!     test        16   50.0000    begin boxcar weighting on this
iteration.
!     test        17    2.0000    give zero weight to resids gt
this*stand. dev
!Jeffrey's Weighting
!     test        18   50.0000    begin jeffreys weighting on this
iteration.
!     test        19    0.0500    use jeffreys weighting only if rms gt
this.
!     test        20    0.0500    mu of jeffreys weighting funct.

!     test        21    9.0000    maximum number of iterations.
reset test        21   20.
!     test        22   35.0000    limit change in focal depth to this
(km).
reset test        22   20.
!     test        23    0.7000    if delz put eq above surface, move
this fraction
!                                 of the way to the surface.
!     test        24   35.0000    limit change in epicenter to this.
(km)
!     test        25   40.0000    fix depth if epicentral change gt
this. (km)
reset test        25  150.
!     test        26    0.0025    stop iterating if sq of adjustment lt
this.
reset test        26     .00001
!     test        27   20.        if global deep solution converges
below this depth
!                                 continue at depth 1/2 way between
this depth
!                                 and the surface.
!     test        28    0.0000    for fixed hypo on plane, set = plunge
!                                 azimuth.  if neg. continue as free
sol.
!                                 see test(30) and test(47) also.
!     test        29    -.1       set std err of res=+this if degrees
of
!                                 freedom =0 or =-this if this lt 0.
!     test        30    0.0000    if positive: dip of plunge vector for
epi. fixed on
!                                 plane.  see test(28) & (47) also.
!                                 if negative: fix epicenter and solve
for origin and z.
!                                   if test(28) is neg, continue with
free solution.
!     test        31   -1.1500    duration magnitude c1, constant
!     test        32    2.0000    duration magnitude c2, *log((f -
p)*fmgc)
!     test        33    0.0000    duration magnitude c3, *delta
!     test        34    0.0000    if not 0, scale the normal equations
!     test        35    0.0010    minimum damping of normal equations
reset test        35    0.00001
!     test        36  100.0000    maximum first trial depth if computed
from
```

```
!                                   p-arrival times.
!     test          37    3.0000    if termination occurs before this
iteration,
!                                   set iteration number to this and
continue.
reset test          37    5.
!     test          38    0.0000    if this =1, run all with and then
without s/
!                                           =2, run with s/
!                                           =3, run without s/
!                                           =4, fix all at starting
hypocenter, and use s.
!                                          neg, use s to fix origin.
reset test          38  2.0
!     test          39    1.0000    multiply the s and s-p weights by
this factor.
!     test          40    0.0070    duration magnitude c4, *depth
!     test          41    0.0000    if this =1, print opt. ge 1, & sum
opt. =+ or
!                                   -1, then write sum record each
itteration.
!     test          42   75.        global solution deep starting depth
(km wrt sea level)
!     test          43    0.0000    duration magnitude c5, *(log((f -
p)*fmgc)**2)
!usgs uses test(44) = 1.0
!uagi uses test(44) = 0.0
!     test          44    0.0000    if =1 rerun debug eqs with critical
sta/
!                                      =2 continue iter with crit sta/
reset test          44    1.0
!     test          45    0.1379    x scale factor for focal mechanism
plot
reset test          45    .10606
!     test          46    0.0000    xfar set ge dist of test(46)th
station + 10.
!                                   if lt 0 then fill gap.
reset test          46  -15.
!     test          47    0.0000    wt for fix on plane.  see test(28)
and (30).
!     test          48              not used.
!     test          49    0.0000    if .ne. 0 calculate vp/vs ratio;
!                                   if abs val >1 make wadati plot;
!                                   if neg, use wadati origin in
solution.
reset test          49    1.
!     test          50    0.        compute this number of fixed depth
!                                   solutions, for checking rms vs z.
!     test          55              default century, if not specified
within data
reset test          55    19.
!
!  printer option       summary option            magnitude option
!
!  no event output  -1
!  final solution    0   no sum records     0      use xmag           0
!  one line per iter 1   summary records    1      use fmag           1
```

```
!  sta res each iter 2   sum + archive file 2      use (xmag+fmag)/2   2
!  regres each iter  3   archive file       3      prefer fmag/xmag    3
!                        'corrected' input  4      prefer xmag/fmag    4
!                                                  if neg use fms not
fmp

printer option     0

summary option     2

magnitude option   4

!  quality option
!  no summary      0
!  a               1
!  a & b           2
!  a, b, & c       3
!  a, b, c, & d    4
quality option     4

select delays        1

global              1
compress option     0

! do not use summary record from previous run as starting
! location for next run (ignore summary rec = 0)
ignore summary rec  0

! turn off missing stations option with a 1:
missing stations    0

! end of headopts.prm
```

6. Headopts.vol file

```
! For volcano processing, jump to headopts.prm (the network
! processing control file) and then jump to headopts.vol
! (this file) for the special modifications used for routine
! volcano processing.   jcl 3/25/95
!
header content       BOTSWANA Network Processing
!
reset test          1   1.6800
!
!     test          5   -1.0000    first trial depth in kilometers,
unless neg.
!                         aeic uses 30.0, avo uses 5.0
reset test          5   5.0
!
!     test          6   0.0000     radius for aux rms values. if neg
cont
!                                  iteration at most neg point.
!                         aeic uses 0.0, avo uses -1.0
reset test          6   0.0
!
reset test          7    -1.0000
```

```
!
!     test         21    9.0000    maximum number of iterations.
!                        aeic uses 20.0, avo uses 15.0
reset test         21   20.
!
!     test         22   35.0000    limit change in focal depth to this
(km).
!     test         22   20.0       aeic uses 20.0, avo uses 3.0
reset test         22    3.0
!
!     test         27   20.0       global solution: if deep solution
converges
!                                  below this, then continue with
z=this/2.0.
!                        aeic uses 20.0, avo uses 4.0
reset test         27    4.0
!
!     test         28    0.0000    for fixed hypo on plane, set = plunge
!                                  azimuth.  if neg. continue as free
sol.
!                        aeic uses 0.0, avo uses -1.0
reset test         28    -10.
!
!     test         29    -.16      set std err of res=+this if degrees
of
!                                  freedom =0 or =-this if this lt 0.
!                        changed from -.1 to -.07 on 1/21/92  jcl
!                        aeic uses -0.1, avo uses -0.07
reset test         29   -.16
!
!     test         42   75.0       global solution deep starting depth
(km wrt sea level)
!                        aeic uses 75.0, avo uses 15.0
reset test         42   15.0
! end of headopts.vol
```

7. HYPOELLIPSE Control file

```
! headopts.prm and headopts.vol contain the setup parameters
! for running HYPOELLIPSE.
jump headopts.prm
jump headopts.vol
!
! crustal.prm specifies the velocity model.  The first
! model, which is the one that will be used, shows how to set
! up a linear increase over a halfspace.  The second model
! illustrates a multilayer velocity model.
jump crustal.prm
!
! caldata.prm contains the calibration parameters for the
! Akutan stations.
! for pc version use caldata.prm
! uofacal option    caldata.prm
! for unix version caldata.bin
uofacal option    caldata.bin
!
! Constants noprint = 1 will cause documentation of the
```

```
! parameter values, crustal model, station locations, etc
! to be added to the output (.out) file.  Note that if the
! same parameter value it specified more than once, the last
! setting will be the one used (in this case the value will
! be set to 1).
constants noprint    0
constants noprint    1
!
! Printer option 1 adds a blow by blow description of
! every iteration step and is useful for debugging purposes.
! Reverse the order of the following records to turn this
! option on.
printer option       1
printer option       0
tabulation option    4
!
begin station list +1 20140805
jump akutan.sta
arrival times next
jump akutan.pha
```

8. HYPOELLIPSE output file

```
*** Hypoellipse: PC/Non-Xpick/Y2K version 3.9 11/1/2001  ***
  Configured for up to  140 stations in station list
  and up to   70 records per earthquake.
  Run on 2016/11/13 at 20:25
 jump headopts.prm
 arrival-time record blank source fields will be assumed to be source
"d"
                                          itc botswana network
processing parameters

 input extra calibration curves.

 qspa( 9) -4.07-3.74-3.47-3.04-2.60-2.35-2.07-1.71-1.42-1.14-0.88-0.65-
0.43-0.20 0.00 0.20 0.39 0.57 0.73 0.85
           0.94 1.02 1.11 1.19 1.29 1.38 1.46 1.54 1.62 1.68 1.69 1.67
1.54 1.39 1.09 0.86 0.56 0.23-0.34-0.66
 select delays based on closest station.
 global minimum search turned off
 compress printed output.  code =  0

 ignore sum code =     0
 (ignore starting locations on summary records)
 scan for missing stations.  code = 0
 subroutine input1 found end of file on unit    12
 jump headopts.vol


                                      botswana network processing
 subroutine input1 found end of file on unit    12
 jump crustal.prm
 subroutine input1 found end of file on unit    12
 list of stations available for these solutions
                                      botswana network processing
 begin station list +1 20140805
```

```
 station list code =    1
 set up for events starting on 20140805
 name latitude  longitude  elev p thickness p p  pdy1 sdy1  pdy2 sdy2
pdy3 sdy3  pdy4 sdy4  pdy5 sdy5     calr xmgc mgwt fmgc wt
 * continuation  record *      thk 1   2  mod dly
sys                       ps
  polarity stawt teldy code altdy cnyrmody hr
  n01z 24s 30.92  23e 55.97  980 1 0.000.00  1 1  0.00 0.00  0.00 0.00
0.00 0.00  0.00 0.00  0.00 0.00 18  0.00 0.00 1 1 1.00 1010
 *           1.0  0.00       0.00 99999999 99
  n02z 24s  6.81  21e 46.94 1153 1 0.000.00  1 1  0.00 0.00  0.00 0.00
0.00 0.00  0.00 0.00  0.00 0.00 18  0.00 0.00 1 1 1.00 1010
 *           1.0  0.00       0.00 99999999 99
  n03z 22s 59.58  20e 11.73 1313 1 0.000.00  1 1  0.00 0.00  0.00 0.00
0.00 0.00  0.00 0.00  0.00 0.00 18  0.00 0.00 1 1 1.00 1010
 *           1.0  0.00       0.00 99999999 99
  n13z 25s 28.53  22e 51.44 1030 1 0.000.00  1 1  0.00 0.00  0.00 0.00
0.00 0.00  0.00 0.00  0.00 0.00 18  0.00 0.00 1 1 1.00 1010
 *           1.0  0.00       0.00 99999999 99
  n20z 23s 21.78  25e 51.58 1020 1 0.000.00  1 1  0.00 0.00  0.00 0.00
0.00 0.00  0.00 0.00  0.00 0.00 18  0.00 0.00 1 1 1.00 1010
 *           1.0  0.00       0.00 99999999 99
  n21z 25s 48.71  24e 48.05 1158 1 0.000.00  1 1  0.00 0.00  0.00 0.00
0.00 0.00  0.00 0.00  0.00 0.00 18  0.00 0.00 1 1 1.00 1010
 *           1.0  0.00       0.00 99999999 99
 subroutine input1 found end of file on unit    12
                                       botswana network processing

      test variables              description
    standard  reset to
  1    1.7800    1.6800****ratio of p-wave velocity to s-wave velocity.
  2    5.0000    5.8000****lt 0 no elev cor/ =0 use 1st vel/ gt 0 use
this.
  3    0.0000    0.0000    first trial latitude in degrees.
  4    0.0000    0.0000    first trial longitude in degrees.
  5  -99.0000    5.0000****first trial depth in kilometers, unless = -
99.
  6    0.0000    0.0000****sphere rad for aux rms values. if neg cont
iteration at most neg point.
  7   10.0000   -1.0000****minimum number of first motions required to
plot.
  8    0.0000    3.0000****elevation of top of layered models (km).
  9    0.0000    1.0000****if 0 allow neg depths in summary and archive
files.
 10   50.0000    5.0000****apply distance weighting on this iteration.
 11   50.0000  100.0000****xnear = greatest distance with weight of 1.0
 12  100.0000  150.0000****xfar = least distnace with weight of 0.0
 13   50.0000   50.0000    apply azimuthal weighting on this iteration.
 14   50.0000   50.0000    weight out large residuals on this iteration.
 15   10.0000    5.0000****give zero weight to residuals gt this.
 16   50.0000   50.0000    apply boxcar weighting on this iteration.
 17    2.0000    2.0000    give zero weight to residuals gt this*stand.
dev.
 18   50.0000   50.0000    begin jeffreys weighting on this iteration.
 19    0.0500    0.0500    use jeffreys weighting only if rms gt this.
 20    0.0500    0.0500    mu of jeffreys weighting funct.
 21    9.0000   20.0000****maximum number of iterations.
```

```
 22   35.0000    3.0000****limit change in focal depth to this amount
(km).
 23    0.7000    0.7000    if delz would make z neg, set delz = -this*z
(km).
 24   35.0000   35.0000    limit change in epicenter to this. (km).
 25   40.0000  150.0000****fix depth if epicentral change gt this. (km).
 26    0.0025    0.0000****stop iterating if square of adjustment lt
this.
 27   20.0000    4.0000****global opt: if deep solution z > this,
continue with z 1/2 way to surface.
 28    0.0000  -10.0000****for fixed hypo on plane, set = plunge
azimuth.  if neg. continue as free sol.
 29   -0.1000   -0.1600****set std err of res=+this if degrees of
freedom =0 or =-this if this lt 0.
 30    0.0000    0.0000    dip of plunge vector for epi. fixed on plane.
see test(28) & (47) also.
 31   -1.1500   -1.1500    duration magnitude c1, constant.
 32    2.0000    2.0000    duration magnitude c2, *log((f - p)*fmgc).
 33    0.0000    0.0000    duration magnitude c3, *delta.
 34    0.0000    0.0000    if not 0, scale the normal equations.
 35    0.0010    0.0000****minimum damping of normal equations.
 36  100.0000  100.0000    maximum first trial depth if computed from p-
arrival times.
 37    3.0000    5.0000****if termination occurs before this iteration,
set iteration number to this and continue.
 38    0.0000    2.0000****if this =1, run all with and then without s/
=2,run with s/ =3, run without s/ =4, fix hypo
                              / neg, use s to fix origin.
 39    1.0000    1.0000    multiply the s and s-p weights by this
factor.
 40    0.0070    0.0070    duration magnitude c4, *depth.
 41    0.0000    0.0000    if this =1, print opt. ge 1, & summary opt.
=+ or -1, then write sum. record each itteration.
 42   75.0000   15.0000****global opt: deep starting z wrt top of model.
 43    0.0000    0.0000    duration magnitude c5, *(log((f -
p)*fmgc)**2).
 44    0.0000    1.0000****if =1 rerun debug eqs with critical sta/ =2
continue iter with crit sta.
 45    0.1379    0.1061****x scale factor for focal mechanism plot.
 46    0.0000  -15.0000****xfar set ge dist of test(46)th station + 10.
if lt 0 then fill gap.
 47    0.0000    0.0000    weight for fix on plane.  see test(28) and
(30).
 48    6.5000    6.5000    half-space velocity for first trial location.
 49    0.0000    1.0000****if .ne. 0 calculate vp/vs ratio; if abs val
>1 make wadati plot; if neg, use wadati origin in solution.
 50    0.0000    0.0000    for exploring rms space, compute this number
of fixed depth solutions (up to 22).

 51 1000.0000 1000.0000    for epicentral distance beyond this, use
first travel-time table.
 52 2800.0000 2800.0000    Wood Anderson static magnification assumed
for local magnitude determination.
 53    1.0000    1.0000    if .eq. 1 stations with 4-letter codes
ending' e or n treated as horizontals.
 54  200.0000  200.0000    if 1st computed trial location > this (km)
from' closest station, start at closest station.
```

```
 55   19.0000   19.0000****assumed century for events without summary'
record.

 weight option - relative standard errors for code:   0      1      2
3
                                                      1.000  5.000 10.000
20.000

 printer option    0   summary option     2      magnitude option    4
tabulation option  4

 no event output  -2
 one line/eq      -1
 final solution    0   no sum records     0      use xmag            0
no summary        0
 one line per iter 1   summary records    1      use fmag            1
a                 1
 sta res each iter 2   sum + archive file 2      use (xmag+fmag)/2   2
a + b             2
 regres each iter  3   archive file       3      prefer fmag /xmag   3
a,b + c           3
                       "corrected" input  4      prefer xmag /fmag   4
a,b,c + d         4
                                                 if neg use fms not fmp
positive/q from std errors

negative/q from sol+sta
 u of a cal data file:  caldata.bin
 make compensating change in layer below variable layer.


       velocity model  1
   layer  velocity     depth   thickness    vpvs
           km/sec       km         km

     1       5.800     0.000    20.000     1.680
     2       6.500    20.000    18.000     1.710
     3       8.040    38.000    22.000     1.730
     4       8.050    60.000  1000.000     1.730


 the next model is for s only:


       velocity model  2
   layer  velocity     depth   thickness    vpvs
           km/sec       km         km

     5       3.452     0.000    20.000     0.000
     6       3.801    20.000    18.000     0.000
     7       4.647    38.000    22.000     0.000
     8       4.653    60.000  1000.000     0.000
 jump to akutan.pha


 detected end of file prior to final instruction record.
 check input data for completeness.
```

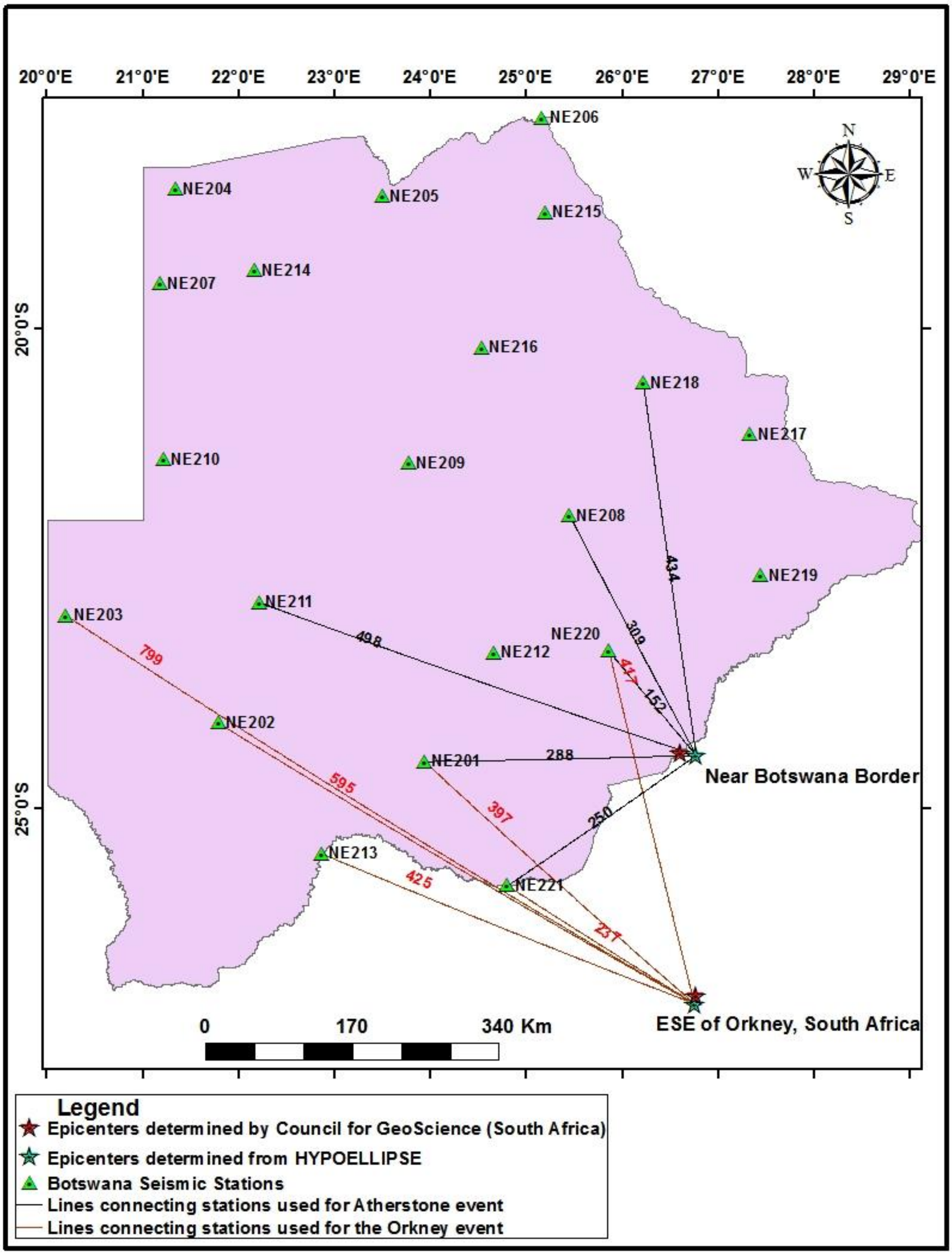
```
 jump back to main input stream.
                                                            --------------------------
--------------------------------------
                                                            --------------------------
--------------------------------------
                                                            --------------------------
--------------------------------------
 14/08/05    10:23        botswana network processing
 bi-weight vp/vs =    2.220 +/- 0.063 based on     5 stations with p and
s
        -az/dp--step---se =az/dp==step===se -az/dp--step---se
        259/21 -55.8 2.12   4/32 -84.1 2.46 142/50 -345. 28.3
 C*       YrMoDyHrMn P-Sec      S-Sec

 horizontal and vertical single variable standard deviations (68% - one
degree of freedom; max 99 km)
       seh =   1.19             seh =   9.81             sez =  11.60
quality = d
       az  =  -128.             az  =   -38.

 se of orig =   0.41; # of iterations =  24; dmax =     795.43; sequence
number =
 event type = " "; processing status = " "
 s minus p interval for closest station =      29.70

    date    origin      lat      long    depth    mag no d1 gap d  rms
avwt   se
 19140805 1022 39.37 27s 2.46  26e44.80  -3.00        11237 306 1 7.8472
1.00  0.16
                    27.0410   26.7466
    seh  sez q sqd  adj in nr   avr  aar nm avxm mdxm sdxm nf avfm mdfm
sdfm   vpvs
    9.8 11.6 d d d 0.11 10 12 0.000 7.13  0            0.0  0
0.0  2.220
 ***> n02n is not on station list, so next record  will not be used:
n02  n   140805102353.50        140.8

                     -- travel times and delays --
  stn c pha remk p p-sec s-sec resid  std-er   dist  azm ain    tc c
vthk  ttob-ttcal-dlay-edly=resid rmk stn pha sources
  n21 z     ez 0   9.800       -6.87    0.17  237.1  305  46       1
30.43 37.31          -6.87     n21
  n21 z s   0            39.5  -3.73    0.17              48       2
60.13 63.86          -3.73     n21 s
  n01 z     ezd1 d 29.30       -7.28    1.00  397.4  314  46       1
49.93 57.22          -7.28     n01
  n01 z s   0            85.6   7.92    0.20              48       2
106.23 98.32           7.92     n01 s
  n20 z     iz 0   31.80       -7.24    0.21  417.1  347  46       1
52.43 59.67          -7.24     n20
  n20 z s   0            87.8   5.87    0.21              48       2
108.43102.56           5.87     n20 s
  n13 z     ezd0 d 33.50       -6.58    0.21  425.4  293  46       1
54.13 60.72          -6.58     n13
  n13 z s   0            92.4   8.67    0.21              48       2
113.03104.37           8.67     n13 s
```

```
  n02 z     ezd3 d 53.50       -7.66    6.89  594.8  302  46       1
74.13 81.80          -7.66     n02
  n02 z s   8            141.  20.80    0.34             48       2
161.63140.83          20.80     n02 s
  n03 z     iz 4   17.20       -9.33   -----  798.6  303  46       1
97.83107.17          -9.33     n03
  n03 z s   1            153.  48.91    7.08             48       2
233.63184.72          48.91     n03 s

                                     -- magnitude data --
  stn c source sys    c10   amx gr ink     amf    per   unit/mm  gnd mot
u xmgc xmag  fmp fmag
1  date    origin    lat n    long w    depth    mag no gap dmin  rms
  140805 1022 39.37 27- 2.46  26-44.80  -3.00   0.00 11 306237.1 7.85

                                                                  i

                                                               *     *
                                                        *
*
                                                  *
*

                                            *
*


                                        *
*


                                   *
*


                                *
*
                                                   d

                                                d
                              *
*
                                               d


                             *
*

                             -                                    *
-

                             *
*
```


1
i
i
n01
n02

```
                              *
*
                                               n13


                             *
*
                             -                                    *
-
                             *
*


                              *
*


                                *
*

                                   *
*

                                        *
*

                                            *
*
                                                  *
*
                                                        *
*
                                                               *     *

                                                                  i

 xxxx this record skipped - out of place xxxx


 sound bell □□□
  completed reading input phase file
 average rms of all events =    7.84722
 average vp/vs ratio =       2.22 for    1 events.  standard deviation
of ratio =       0.00

 ***** class/     a     b     c     d total *****

      number/   0.0   0.0   0.0   1.0   1.0
```

```
  percentage/   0.0   0.0   0.0 100.0

   include only class d and better in the following statistics.

          ----------- p residuals --------------    ----------- s
residuals -------------
           no event wting        event wting         no event wting
event wting
 station  n  wt  ave   sd     n   wt  ave   sd      n  wt   ave  sd
n   wt   ave  sd    station
    n01z   1 0.0-7.284 0.000   1  0.2-7.284 0.000    1 0.6 7.917 0.000
1  4.5 7.917 0.001    n01
    n02z   1 0.0-7.662 0.000   1  0.0-7.662 0.001    1 0.220.801 0.000
1  1.520.801 0.000    n02
    n03z   0 0.0 0.000 0.000   0  0.0 0.000 0.000    1 0.048.911 0.000
1  0.048.911 0.000    n03
    n13z   1 0.6-6.582 0.000   1  4.0-6.582 0.001    1 0.6 8.666 0.000
1  4.0 8.666 0.002    n13
    n20z   1 0.6-7.239 0.000   1  4.2-7.239 0.001    1 0.6 5.871 0.000
1  4.2 5.871 0.000    n20
    n21z   1 0.9-6.871 0.000   1  6.5-6.871 0.001    1 0.9-3.731 0.000
1  6.5-3.731 0.001    n21

           s-p residuals        x-mag res       f-mag res
 station  n  wt  ave   sd     n  ave   sd     n  ave   sd
 irelo =  0  nreloc =  0
```


20°0'E
21°0'E
22°0'E
23°0'E
24°0'E
25°0'E
26°0'E
27°0'E
28°0'E
29°0'E
20°0'S
25°0'S
N
S
W
E
NE206
NE204
NE205
NE215
NE207
NE214
NE216
NE218
NE217
NE210
NE209
NE208
NE219
NE203
NE211
NE220
NE212
NE202
NE201
NE213
NE221
434
309
498
799
417
152
288
595
397
250
425
231
Near Botswana Border
ESE of Orkney, South Africa
0
170
340 Km
Legend
Epicenters determined by Council for GeoScience (South Africa)
Epicenters determined from HYPOELLIPSE
Botswana Seismic Stations
Lines connecting stations used for Atherstone event
Lines connecting stations used for the Orkney event

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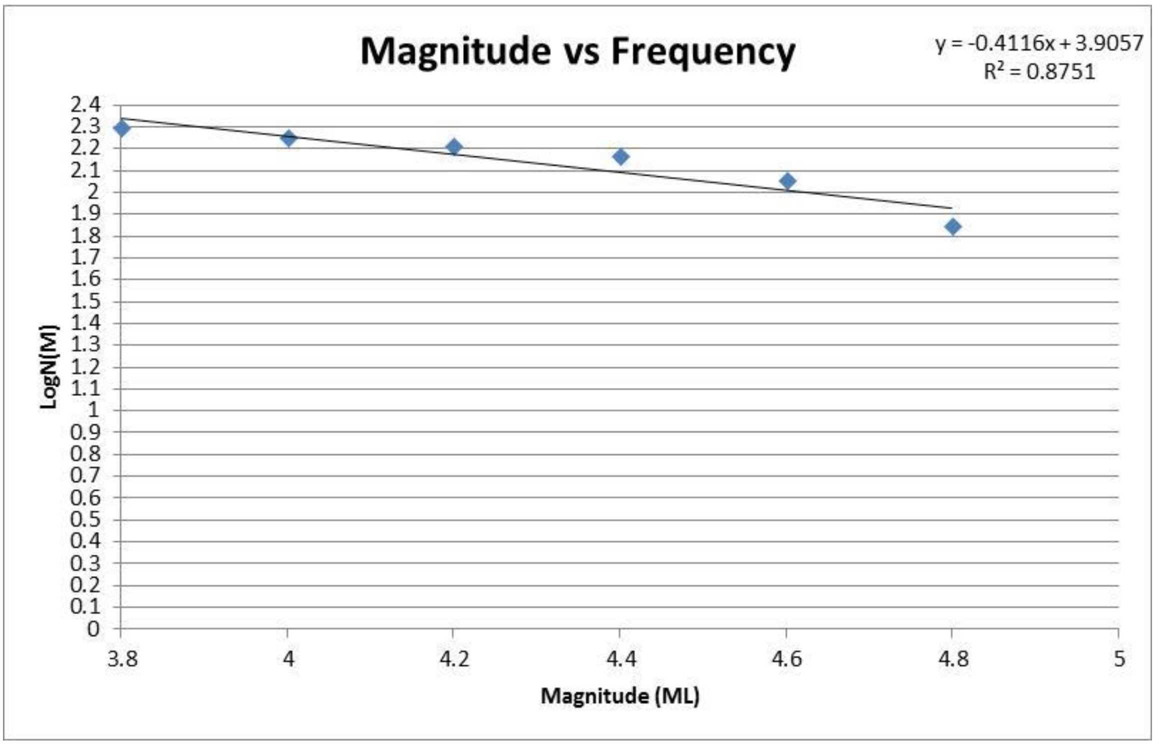
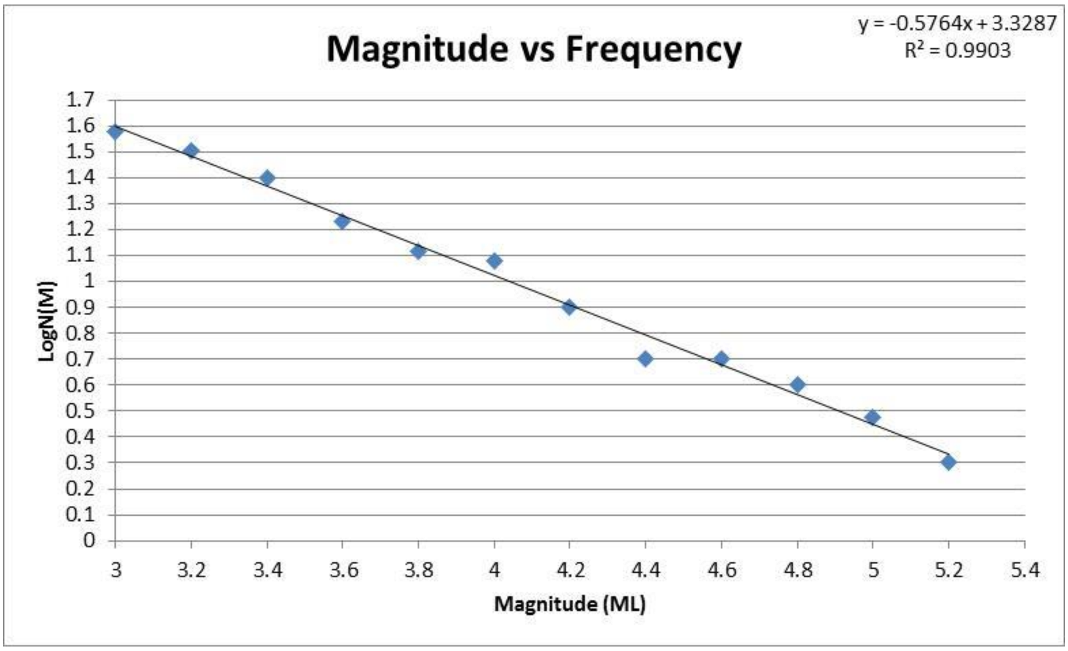
Appendix B: Magnitude recurrence plot for the 15 source zones used in this study

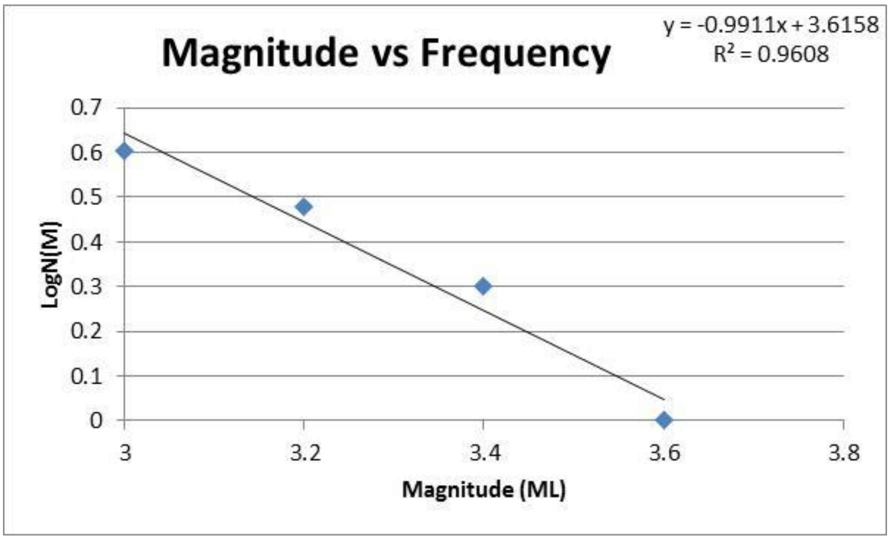
Zone 1



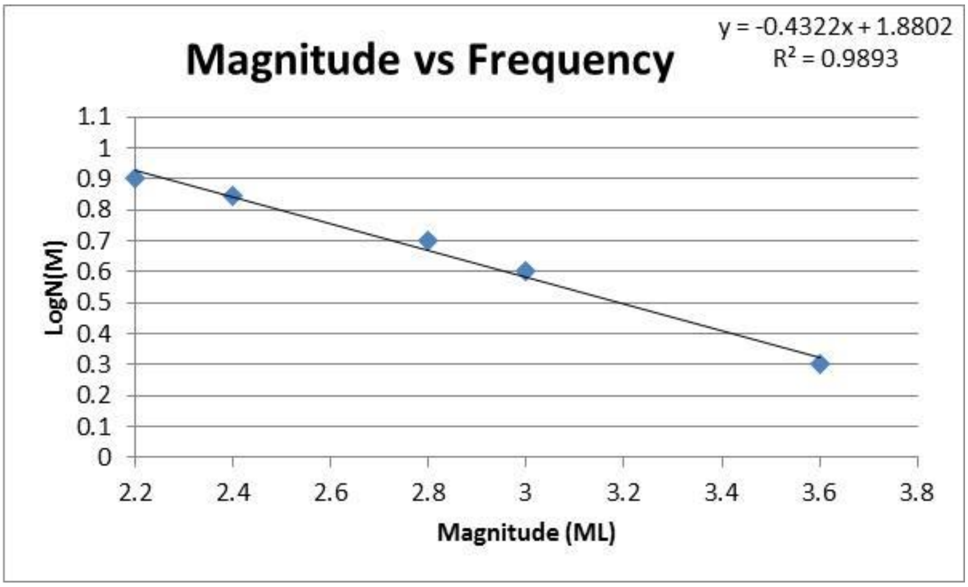
Zone 2



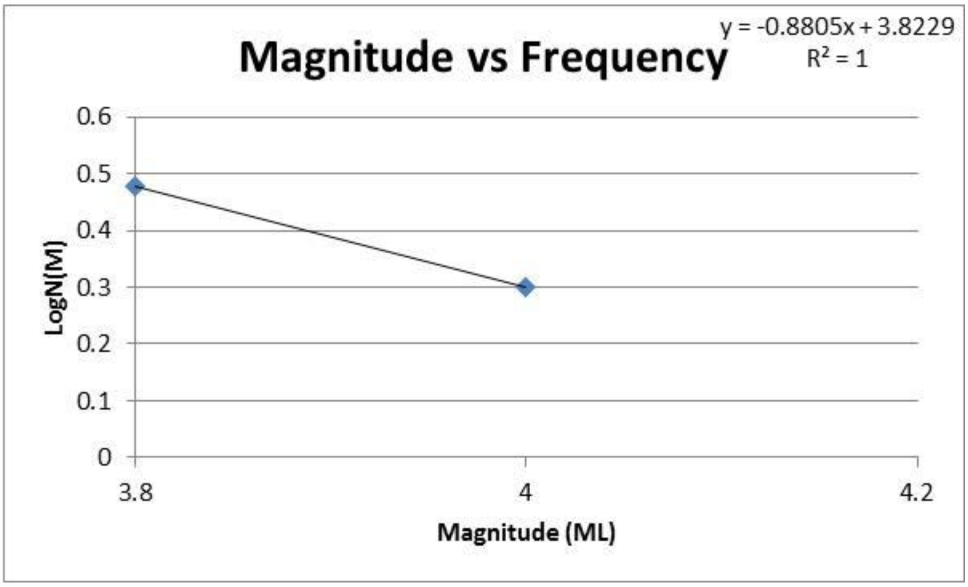
Zone 3


Magnitude vs Frequency
y = -0.9911x + 3.6158
R² = 0.9608
LogN(M)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
3.2
3.4
3.6
3.8
Magnitude (ML)

Zone 4

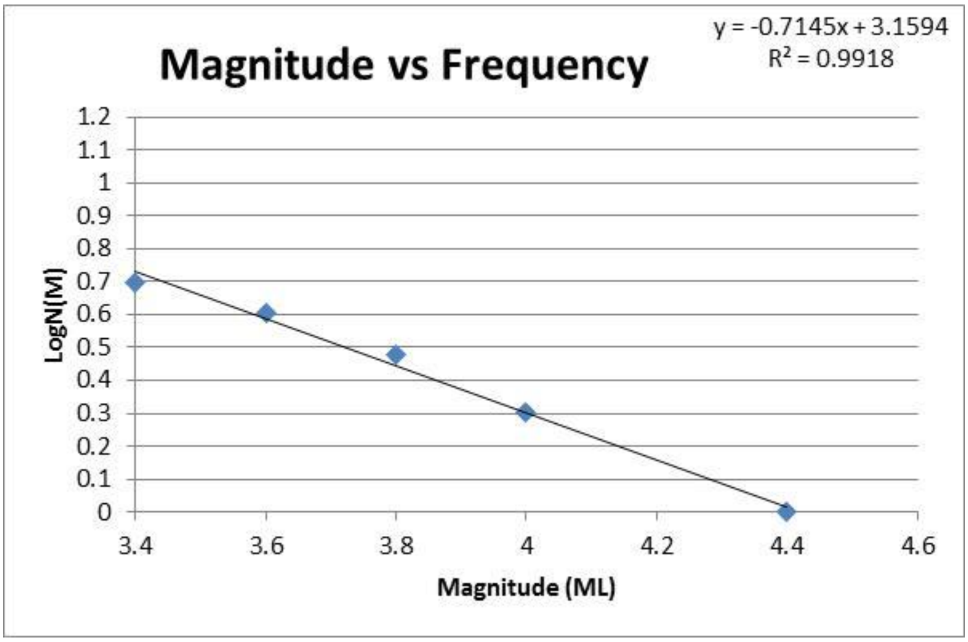

Magnitude vs Frequency
y = -0.4322x + 1.8802
R² = 0.9893
LogN(M)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
Magnitude (ML)

Zone 5



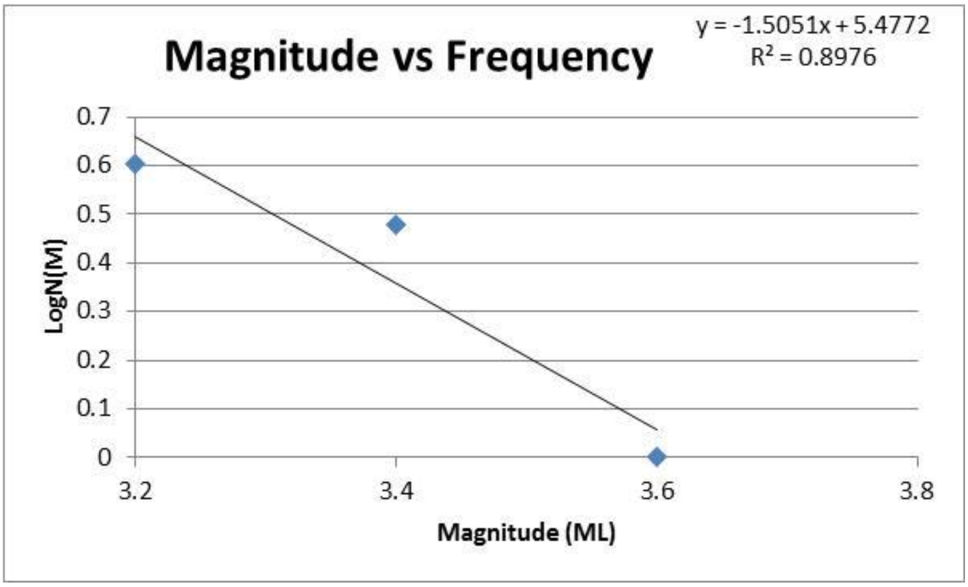
Magnitude vs Frequency
y = -0.8805x + 3.8229
R² = 1
LogN(M)
0.6
0.5
0.4
0.3
0.2
0.1
0
3.8
4
4.2
Magnitude (ML)

Zone 6

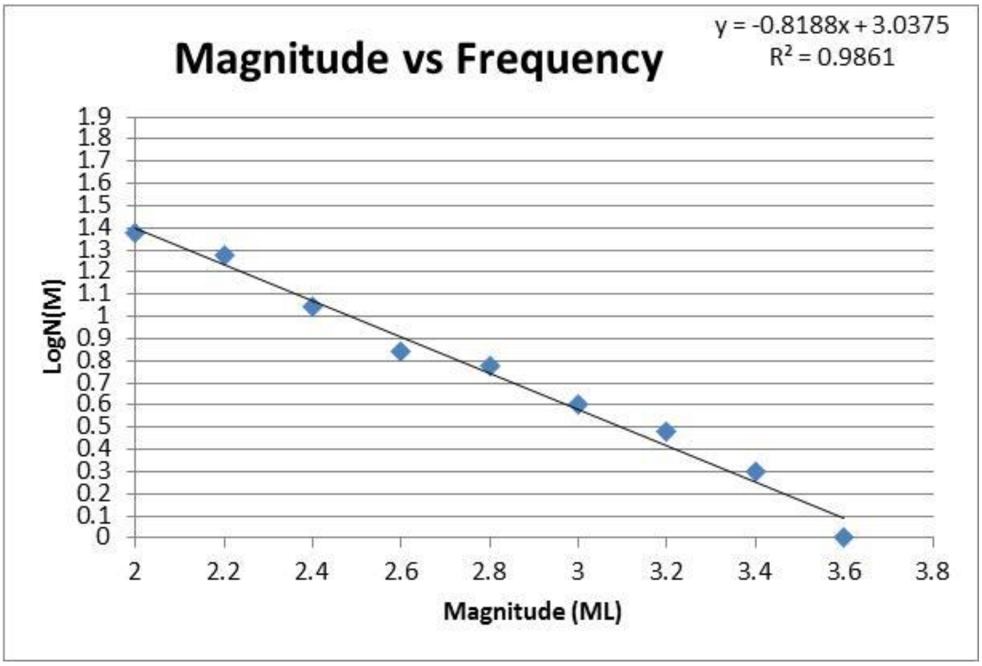


Magnitude vs Frequency
y = -0.7145x + 3.1594
R² = 0.9918
LogN(M)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3.4
3.6
3.8
4
4.2
4.4
4.6
Magnitude (ML)

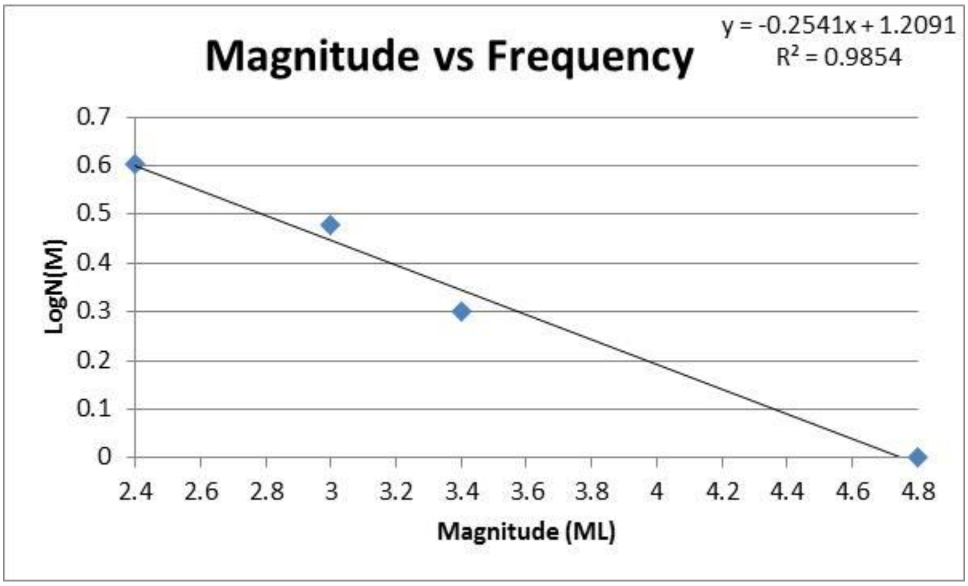
Zone 7


Magnitude vs Frequency
y = -1.5051x + 5.4772
R² = 0.8976
LogN(M)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3.2
3.4
3.6
3.8
Magnitude (ML)

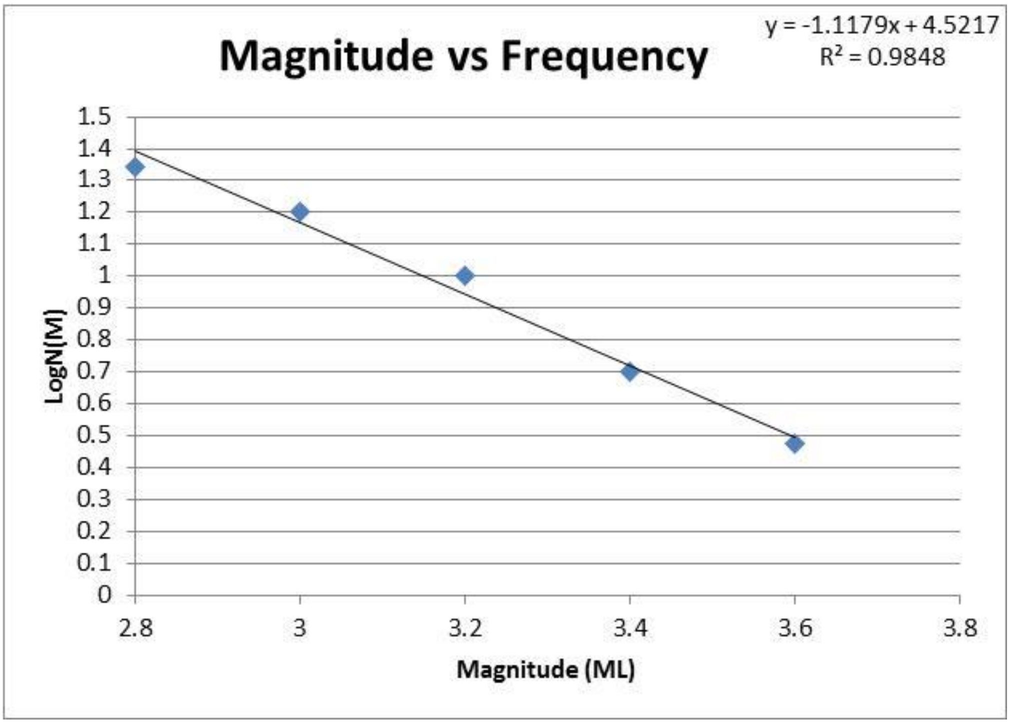
Zone 8


Magnitude vs Frequency
y = -0.8188x + 3.0375
R² = 0.9861
LogN(M)
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
Magnitude (ML)

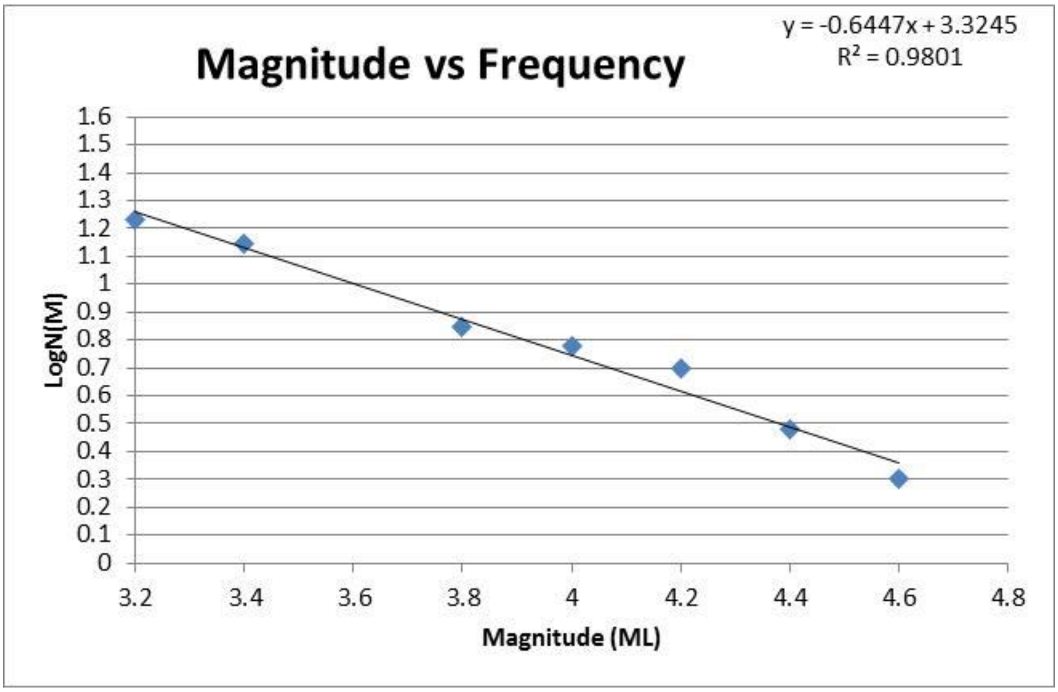
Zone 9



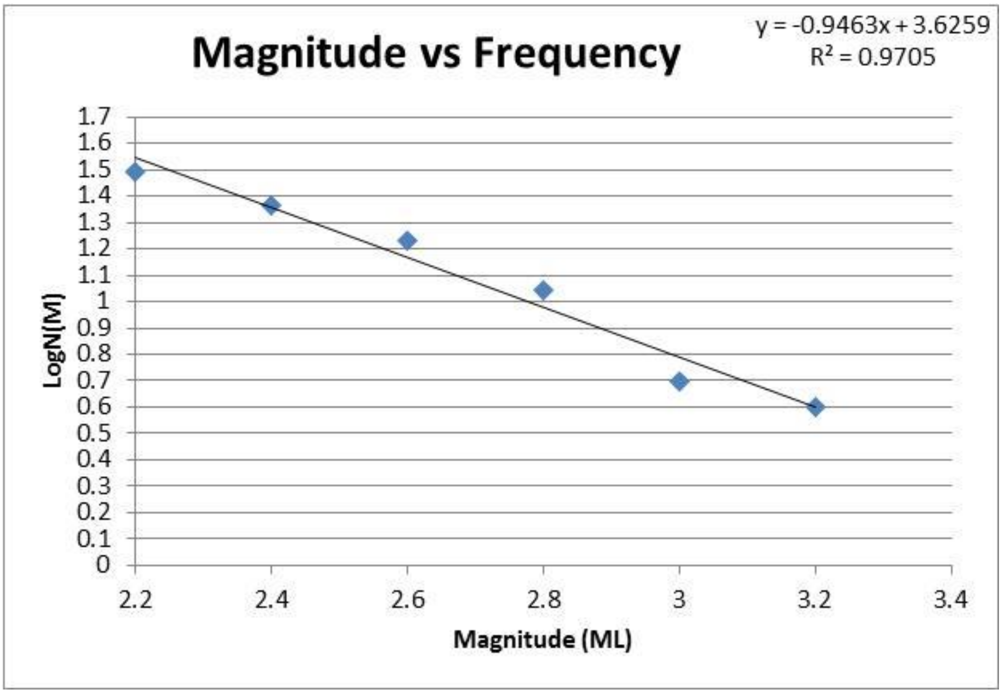
Zone 10



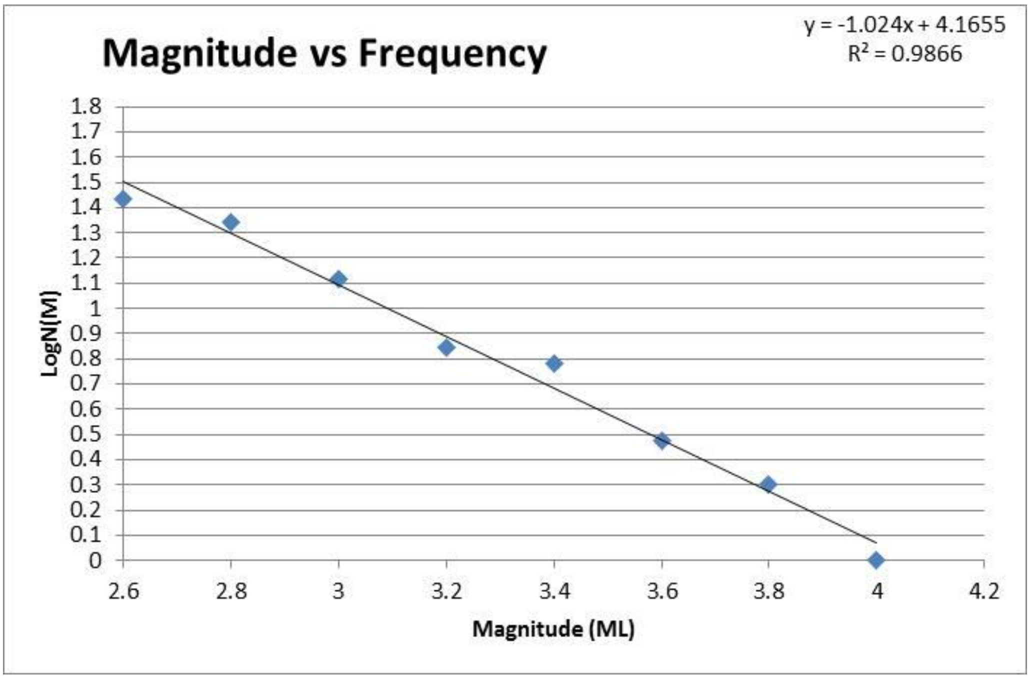
Zone 11



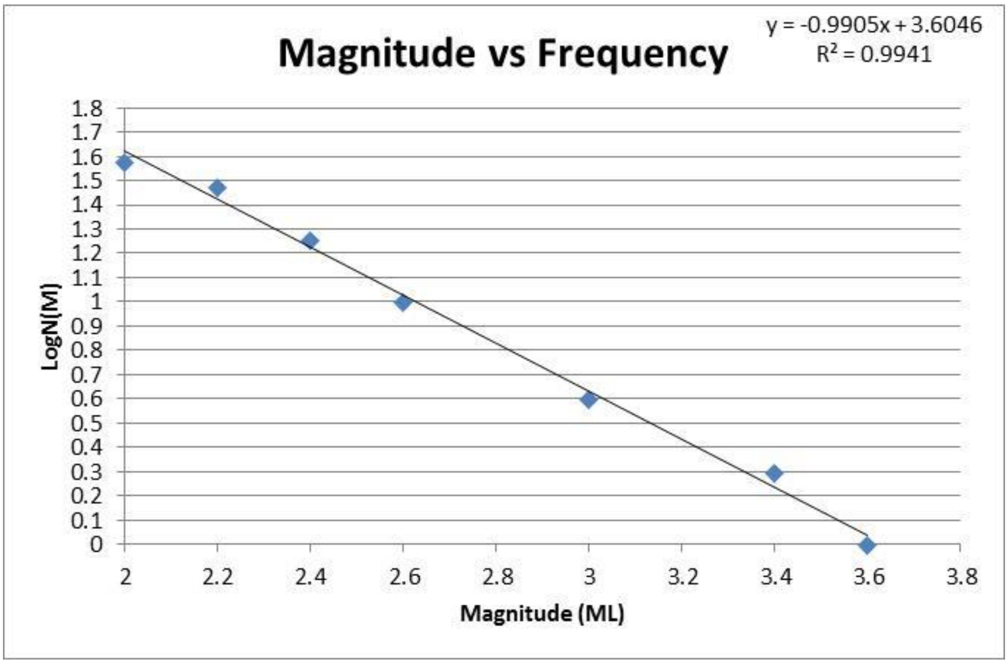
Zone 12



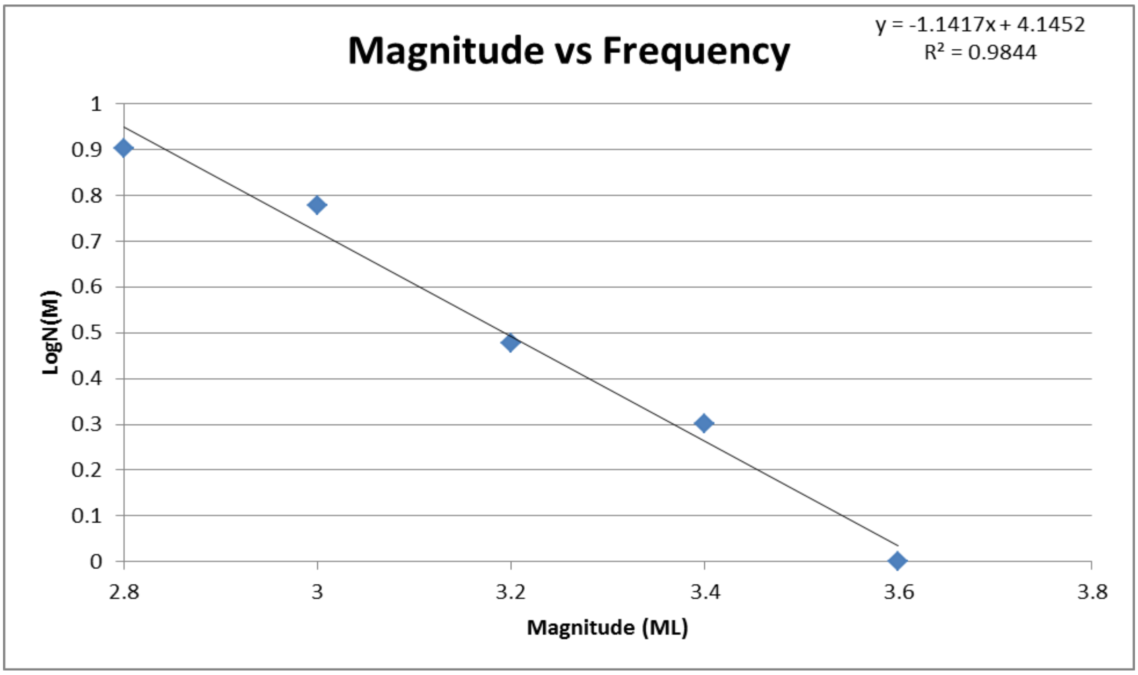
Zone 13



Zone 14



Zone 15


Magnitude vs Frequency
y = -1.1417x + 4.1452
R² = 0.9844
LogN(M)
Magnitude (ML)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2.8
3
3.2
3.4
3.6
3.8

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