

**SEISMIC SOURCES, SEISMOTECTONICS AND
EARTHQUAKE RECURRENCE FOR THE KZN COASTAL
REGIONS**



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DECLARATION 1 - PLAGIARISM

I, Mayshree Singh, declare that

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Mayshree Singh

18 March 2016

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DECLARATION 2 - PUBLICATIONS

All the publications represent research completed and compiled in their entirety by the author with Dr. Mulemwa Akombelwa and Dr. Rodney Maud providing technical suggestions and amendments. Where technical assistance was received this has been duly acknowledged in the relevant sections.

Published peer reviewed journal paper:

Singh, M., Akombelwa, M. and Maud, R. (2014). Analysis of possible sources of some unregistered historical earthquake tremors that affected the KwaZulu-Natal coastal regions of South Africa for seismotectonic investigations. *Natural Hazards* (2015). 75:2279-2289. DOI 10.1007/s11069-014-1425-8. (See Chapter 2 and Appendix 5.6)

Submitted peer reviewed journal papers:

Singh, M., Akombelwa, M. Andreoli M, Brynard H, Maud, R. and Saunders I (2015). Seismotectonic Analysis of Kwa-Zulu Natal, South Africa, Database Assembly and Areal sources interpretation, *SAJG*, under review. (See Chapter 3)

Conference Research Abstracts:

Singh M. (2012) Seismotectonic Analysis for the KZN region of South Africa, Vol 14, EGU 2012-10491 (See Appendix 5.1)

Singh, M., Akombelwa, M. and Maud, R. (2014). Seismotectonic Interpretations of Seismic and Structural data for the KZN Province of South Africa *Africa Array Workshop, Wits University, January 2014* (See Appendix 5.4)

Singh, M., Akombelwa, M. and Maud, R. (2015). Analysis of possible sources of some unregistered historical earthquake tremors that affected the KwaZulu-Natal coastal regions of South Africa for tectonic investigations. *Africa Array Workshop, Wits University, January 2015* (See Appendix 5.5)

Conference Extended Abstracts

Singh, M., Akombelwa, M. and Maud, R. (2013), Combining Structural Domains, Geomorphological Provinces and GPS Data for Seismotectonic Modelling of the KZN Province, SAGA-AEM Conference, July 2013, Kruger National Park, SA (See Appendix 5.2)

Non-Peer Reviewed Article:

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Singh, M., Akombelwa, M. and Maud, R. (2014), Geo-Database compilation for Seismotectonic investigations for the KZN coastal regions, Position IT, July 2014, EE Publishers (PTY) Ltd. (*See Appendix 5.3*)

Mapuranga, V. and Singh, M. (2015). Earthquake recurrence parameters for the KwaZulu-Natal Province. SAGA Conference, September 6-19, 2015, Drakensberg, South Africa. (*See Appendix 5.7*)



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ABSTRACT

Historical earthquake information forms a critical dataset for seismotectonic investigations that can be used for seismic hazard investigations of hazardous and high rise structures and national seismic hazard maps. This study systematically interrogates historical earthquake data for the region from various sources in order to have a better understanding of the origins of the larger earthquakes. Several previously undocumented earthquakes were found that can supplement the national catalogue. Various sources are postulated as origins of these tremors namely local sources located in Mtubatuba and offshore sources like the Mozambique Channel.

A seismotectonic model of the study region is also presented from an analysis of earthquake data, structural and kinematic systems. Geo-spatial data from geology, tectonics, regional geophysical anomalies, historical and instrumental seismicity and kinematics are considered.

For what was once considered as a diffuse seismotectonic region with low levels of seismicity and where insufficient, uncertain and incomplete data existed – we now have datasets that are more complete and have higher levels of accuracy.

Earthquake epicentres from both the historical and instrumental record as well as thermal spring localities correlate with old Jurassic faults. An assembly of a variety of datasets and studies are performed followed by a delineation of respective seismotectonic provinces.

Earthquake recurrence parameters were assessed for the seismic provinces. Many of the provinces had insufficient seismic data to compute parameters. Improved seismic monitoring of the east coast region is required to better characterise the seismic risk.

These results re-emphasize the need to better understand the coastal environment for seismotectonic characterization and to densify the seismic network towards the eastern coastline.

PREFACE

GOD is in all things and all things are possible with GOD in mind....

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CHAPTER 1: INTRODUCTION

1.1 Problem Definition

Devastating earthquakes and tsunamis have shocked the modern world (Table 1.1). These earthquakes have caused large scale damage to the built environment not to mention the high number of fatalities. The KwaZulu-Natal (KZN) coastal region is a fast developing region. This can be seen especially towards the north of the Durban CBD. The KZN is home to 10 million inhabitants with a relatively denser population distribution around the Durban and Pietermaritzburg CBDs. With the increasing amount of investment towards the north coast of Durban, the population distribution will migrate to these areas. These new buildings and inhabitants will then become ‘vulnerable’ to rare, infrequent and potentially devastating natural disasters like earthquakes.

This research is aimed towards developing a seismotectonic model for the KZN coastal region through analysis of the historical earthquake catalogue for the region; geodatabase assembly for the zonation, and lastly assessment of earthquake recurrence parameters for use in seismic hazard assessments.

One of the first steps to understand and plan for an earthquake occurrence is through a seismic hazard and risk assessment of which seismotectonic modelling forms a major component (Figure 1.1).

Terrier et al. (2000) define **seismotectonic analysis** as the analysis of structural, neotectonic and seismological data to establish links between seismicity and current deformation mechanisms, and their effects on certain tectonic structures, with the ultimate goal of delimiting and characterising various seismotectonic units. **Seismotectonic units or zones** correspond to tectonic structures like faults, or to geological and structural bodies of uniform seismicity. The **seismotectonic model**, otherwise known as a seismotectonic map, seismotectonic zonation or seismotectonic provinces will consist of a presentation of all the seismotectonic units identified for the region of interest.

A first-order regional seismotectonic model for SA was developed by Singh et al. (2011) by combining available regional earth science datasets as shown in Figure 1.2. A multidisciplinary geoscientific database was also compiled by them in Singh et al (2009). In their study several gaps were identified in the earth science dataset required for the modelling namely:

- (i) The current number of seismic stations and their configuration allows for a very limited detection capability of the network. As a result the location of earthquake events can be poor, and the ability to detect micro-earthquakes on active structures is rather limited. A denser

network of seismic monitoring stations is required to improve the sensitivity and location accuracy of recorded earthquakes

(ii) A comprehensive study is required to distinguish mining-related earthquakes from earthquakes of natural tectonic origin in the database. Furthermore, analytical techniques should be adopted by custodians of the national network to distinguish these events as they are reported

(iii) Quaternary sediments, especially those providing evidence of neotectonic and paleoseismicity, need to be dated and mapped across the country.

To address these gaps for any country is a mammoth task not to mention the capital, skills and time required. Hence this study is focused towards a smaller research area that will address some of the gaps identified and which can be quite useful for enhancement of the seismotectonic model already developed. It is important to note that no seismotectonic model of this nature for KZN is readily available in the published literature.

1.2 Motivation

The KZN region has been selected for the study area for several reasons. For budgetary reasons appropriate site visits will cost significantly less compared to visits to regions away from the local area. The work can be more focused when the area is much smaller as compared to studying the whole country for example. The KZN province especially towards the northern coastline has had significant growth and investment over the years which make the province now more vulnerable to earthquakes. Lastly, historically fair amount of damage occurred from earthquakes. Historical reports of damage to the KZN coastal areas have been reported since 1932. These earthquakes are reported to originate from different sources even neighboring countries like Mozambique. Note that the damage reported was significantly less compared to the possible damage if a similar earthquake were to occur today. This would mainly be caused by the rapid change in infrastructure and development.

1.3 Aims and Objectives

The aim of this research is to develop a seismotectonic model for the KZN region. Under the framework of this research, it is proposed to refocus attention on the KZN coastal region, increase resolution of data in the study area, and make improvements on the existing datasets and to redefine the boundaries of the regional seismotectonic model using the enhanced datasets.

These objectives were achieved by undertaking the following tasks for the KZN coastal region:

1. Search for missing events in the historical earthquake catalogue – see Chapter 2
2. Analysis of seismic/tectonic sources from historical tremors – see Chapter 2
3. Development of a Geo-Database for use – see Chapter 3
4. Development of a Seismotectonic Model – see Chapter 3
5. Development of an Earthquake Recurrence Model – see Chapter 3

It was extremely difficult logistically to separate findings of Objectives 3-5 in separate publications so all three were organized into one publication and is provided in Chapter 3.

1.4 Research Approach

Each of the objectives outlined above were achieved by using different research methods and will be described separately.

OBJECTIVE 1 Search for missing events in the historical earthquake catalogue – see Chapter 2

The flowchart summarising the methodology for the seismotectonic zonation followed by Singh et al. (2011) is shown in Figure 1.3. The methodology is refined and presented again in Chapter 3. The seismicity data is an essential starting point for Stage 1 Collection and Selection of Base Data. The custodian of the earthquake catalogue for South Africa is the Council for Geoscience (CGS). The preliminary data was obtained from the CGS. It is also possible that earthquakes (especially the historical ones) can be missing in the database so this aspect was investigated further. This work was published in Natural Hazards (see Appendix 5.6). The full paper is included in Chapter 2.

OBJECTIVE 2 Analysis of seismic/tectonic sources from historical tremors – see Chapter 2

The sparse coverage of the seismic network in the east coast of SA makes it difficult to locate the source of tremors or earthquakes occurring here. Other techniques are then used to investigate the

seismic or tectonic sources of these earthquakes. This work was published in Natural Hazards (see Appendix 5.6). The full paper is included in Chapter 2.

OBJECTIVE 3 Development of a GeoDatabase (See Chapter 3)

The methodology illustrated in Figure 1.3 has been revised as a result of this work. However the inputs for the database remain unchanged.

The GeoDatabase includes datasets that contribute to the understanding of

- 1) The Seismic System
- 2) The Structural System and the
- 3) Kinematic System

These datasets include that of geology, geophysics, earth stress, seismicity, neotectonics, topography, structure and anisotropy of the crust and mantle. High resolution datasets were requested from respective custodians (CGS) and various researchers that have published their works. Seismicity datasets were analysed to determine recent stress fields. This work was presented in the Africa Array conference (Appendix 5.4 and Appendix 5.5)

Note that during data collection there was no restriction on the scale of the data to be collected. The reason that scale wasn't a strict parameter at that stage was that all the available base data were being collected. Once potential sources are identified one can then proceed with sourcing or acquiring better resolution data.

OBJECTIVE 4 Development of a Seismotectonic Model (See Chapter 3)

The methodology for the model development was refined to include the kinematic system. The delineation of the respective units was done manually. However a discussion is provided on methodologies available to automate the process. This automation was beyond the scope of this work and certainly an avenue to be explored in future research.

*OBJECTIVE 5 Investigations of Earthquake Recurrence Parameters and Seismic Hazard Implications
(See Chapter 3)*

It is essential to provide earthquake recurrence parameters for each seismotectonic unit. This was done using different analytic procedures. Some challenges that are inherent in this work include the incompleteness of the seismicity datasets and the insensitivity of the national seismic network to detect earthquakes of magnitude less than 3 which are essential for identifying/mapping slow creeping faults/active features. The shortcomings in the resulting model can then be accounted for in the SHA by the use of probabilistic models, hypothetical assumptions and logic trees and is out of the scope of this work.

1.5 Technical and Scientific Contributions

Several new technical and scientific contributions were produced:

- An instrumental earthquake catalogue with focal mechanisms for KZN was developed (by Ian Saunders TUT MSc Thesis under preparation)
- A geodatabase for KZN was created for seismotectonic modelling (by M Singh Chapter 3))
- New historical intensity data points were recorded (by Vuyo Zungu, UKZN Hons Thesis 2013 (Supervised by M Singh) Chapter 2 Table 2.1)
- A database of naturally occurring springs for the KZN province was compiled by UKZN Hons student Londi Shude (Supervised by M Singh), Chapter 3, Figure 3.9.
- A consolidation of the geology and geomorphological evolution of the region over time is presented. This can be developed into a 3D evolution model in future research (Chapter 3 Table 3.1)
- A seismotectonic model for the KZN province was prepared (by Mayshree Singh Chapter 3 Figure 3.13)
- Earthquake recurrence parameters for KwaZulu-Natal Province were calculated for the seismotectonic zones outlined above (by V. Mapuranga and M. Singh. See Chapter 3 and Appendix 5.7).
- A seismic risk analysis for the EThekweni Municipality area was performed by Jennifer Martinez UKZN MSc Thesis (Supervised by M Singh, M Akombelwa and M Chilufya).
- A database of potentially active faults for the KZN region was prepared by Sefako Ngoasheng UKZN BSc Hons Thesis (Supervised by M. Singh)

- A seismotectonic model for the KZN region was developed using the SOM algorithm by Innocent Ngcobo UKZN BSc Hons Thesis (Supervised by M. Singh)
- A database of seismic vulnerability for the Durban CBD was developed by Siyabongwe Tshabalala UKZN BSc Hons Thesis (Supervised by M. Singh)
- The reference database consisting of an Endnote platform, Excel platform and Hardcopy platform was prepared and this comprised of all the research articles and reports cited in this thesis. Due to copyright issues it cannot be made publicly available. Nevertheless these databases will ensure longevity of the research and facilitate easy updating and validating.
- Findings from this research has been presented at scientific meetings (included in the Appendix)

The funding for this project also provided a unique opportunity for collaboration of various scientists and students located in a number of research institutions from a variety of disciplines.

1.6 Structure of the Thesis

Chapter 2 This thesis begins with a review of large historical earthquakes that have affected the province and then searches for seismic sources of some unrecorded seismic tremors that have affected the region

Chapter 3 Provides a summary of the methodological framework that was selected for the seismotectonic zonation, a summary of the geodatabase assembled, a summary of the key aspects of the datasets used, the seismotectonic model

Chapter 4 Summarizes the key results of the previous Chapters and provides recommendations for future research in this field.

The Appendix provides a record of non-peer reviewed and peer-reviewed abstracts, papers and proceedings that originated from this work

Table 1.1 List of some recent and notable earthquakes

Location	Date	Earthquake Size	Damage and Fatalities
Haiti	12 January 2010	Mw 7.0	316 000 killed and 300 000 injured
New Zealand	21 February 2011	Mw 6.3	148 killed
Japan	7 April 2011	Mw 9.0	15,457 deaths 5,389 injured US 300\$billion loss (Japanese National Police Agency 2011)

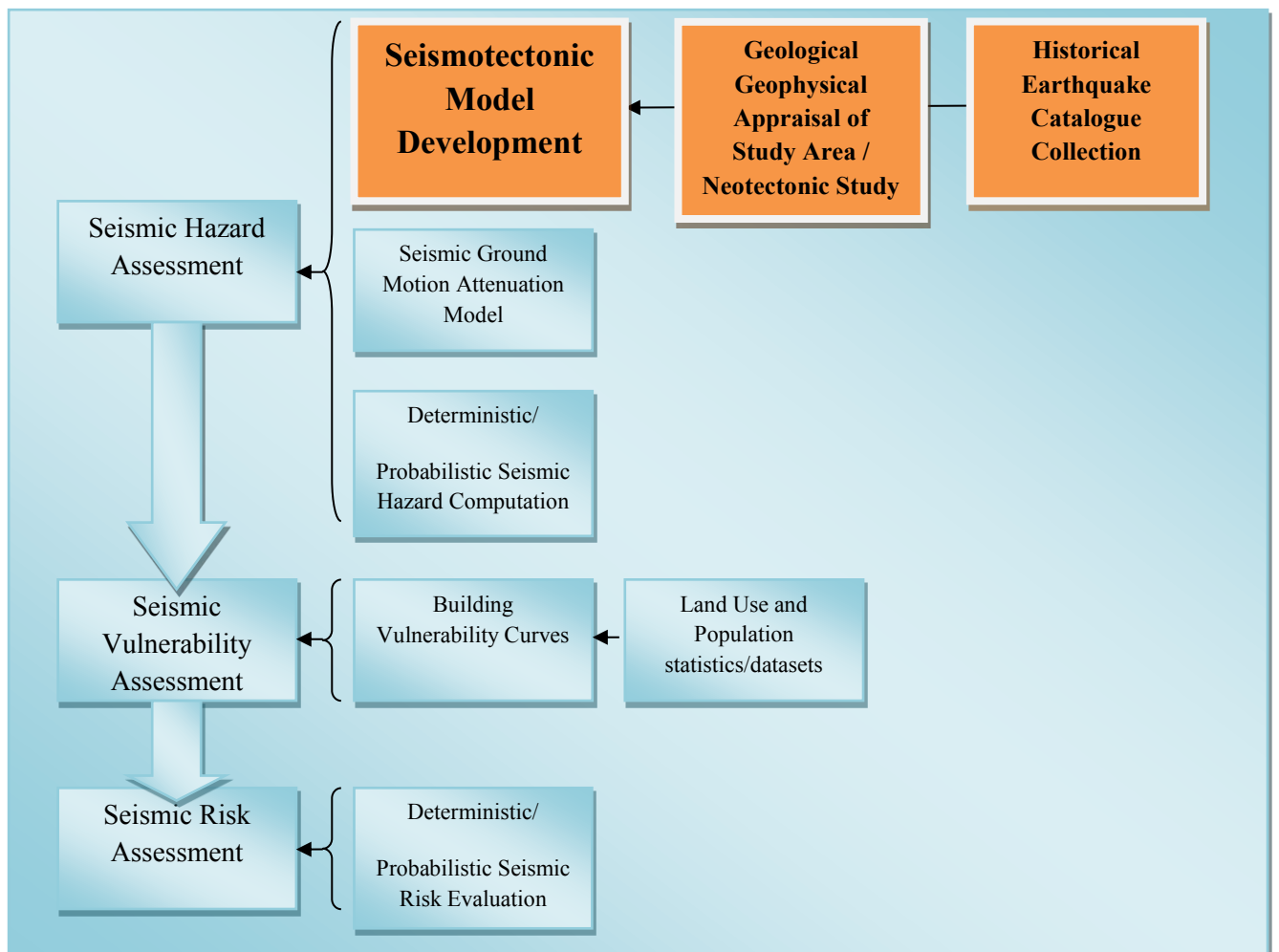


Figure 1.1 Schematic representation of key components of the Seismic Risk Methodology providing context for the seismotectonic component building blocks

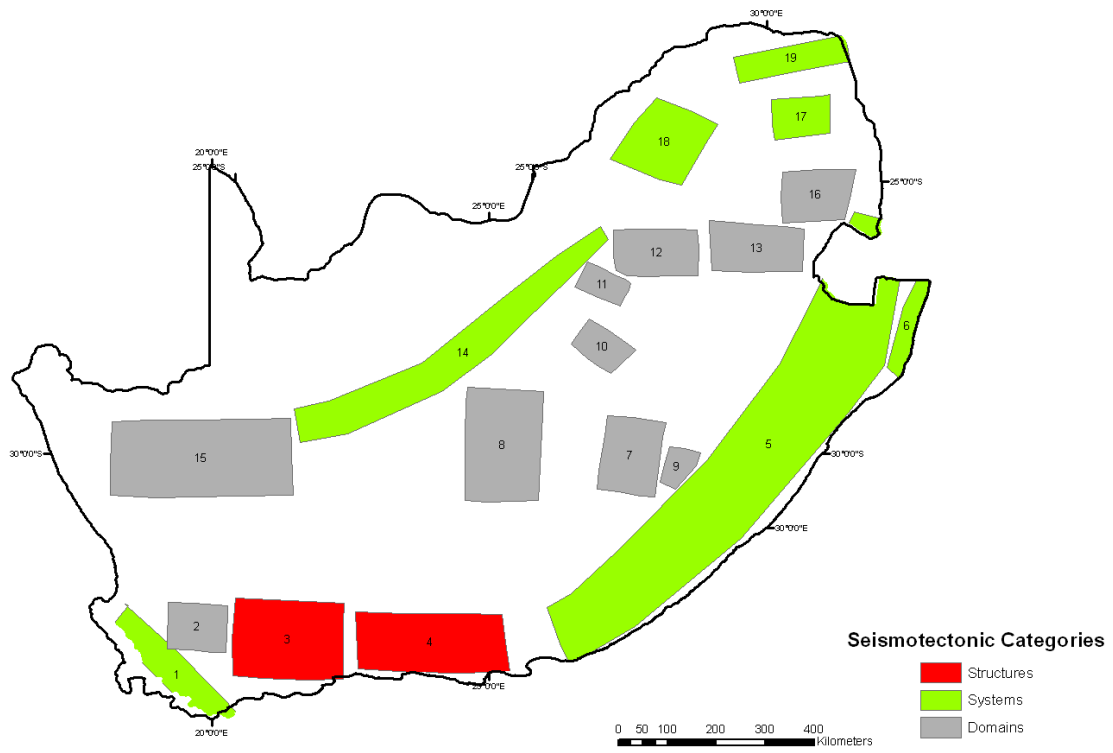


Figure 1.2 Seismotectonic model for South Africa comprising of seismotectonic systems, domains and structures (from Singh et al. 2011).

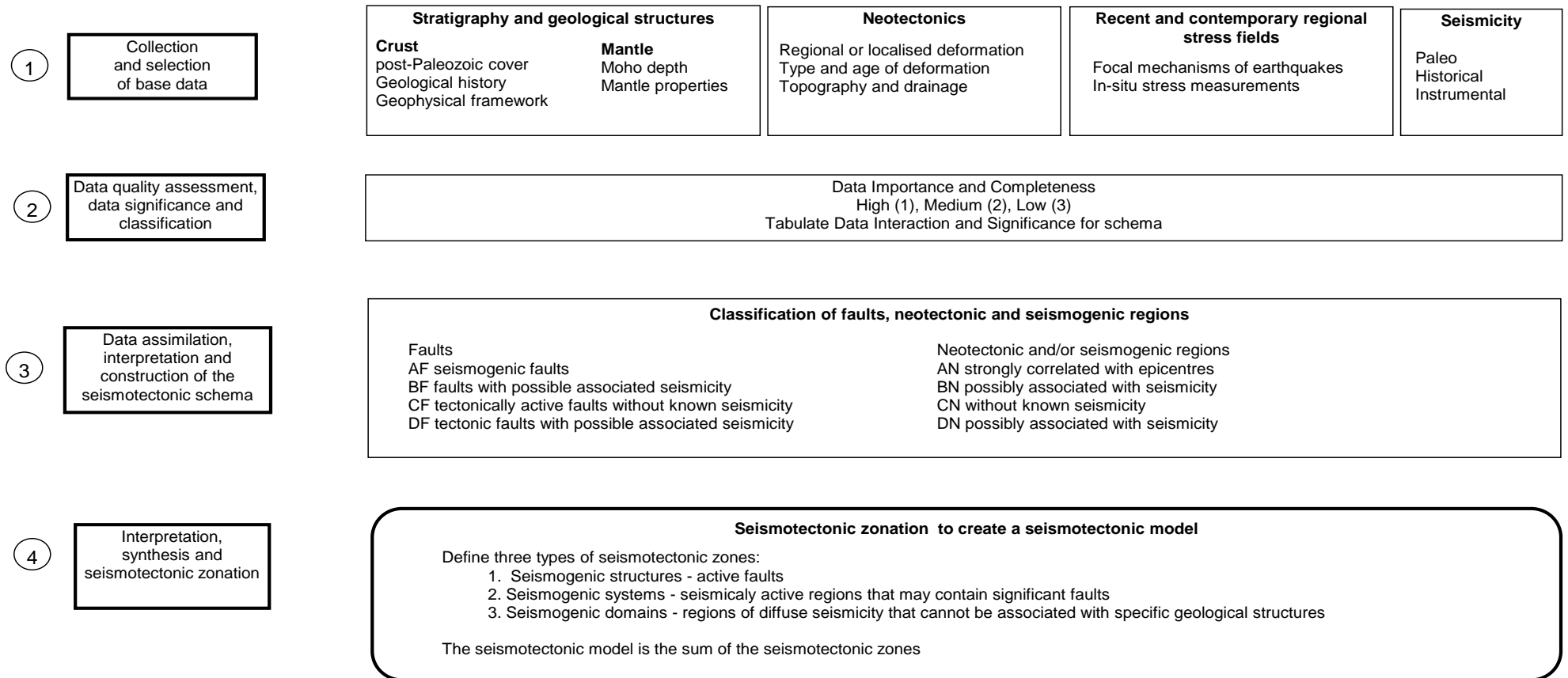


Figure 1.3 Schematic representation of stages in the creation of a regional seismotectonic model (adapted from Terrier et al. 2000).

1.7 References

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CHAPTER 2: ANALYSIS OF POSSIBLE SOURCES OF SOME UNREGISTERED HISTORICAL EARTHQUAKE TREMORS THAT AFFECTED THE KWA-ZULU NATAL COASTAL REGIONS OF SOUTH AFRICA FOR SEISMOTECTONIC INVESTIGATIONS

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Abstract

Historical earthquake information forms a critical dataset for seismotectonic investigations that can be used in seismic hazard investigations of hazardous and high rise structures and national seismic hazard maps. This study systematically interrogates historical earthquake data for the region from various sources in order to have a better understanding of the origins of the larger earthquakes. Several previously undocumented earthquakes were found that can supplement the national catalogue. Various sources are postulated as origins of these tremors namely local sources located in Mtubatuba and offshore sources as in the Mozambique Channel. These results re-emphasize the need to better understand the coastal environment for seismotectonic characterization and to densify the seismic network towards the eastern coastline.

2.1 Introduction

An earthquake catalogue is an important resource that can be used to assess the probability of future occurrences of earthquakes in a given region in order to build seismic resistance into engineering structures. While the instrumental part of the earthquake catalogue is critical for recording earthquakes as they occur the catalogue should also reflect historically recorded events of generally larger magnitudes that usually have occurred less frequently (Ambraseys 1971). Historical seismic records have been compiled into national earthquake catalogues worldwide. Some examples include those for Europe (Rubbia 2004), India (Rao and Rao 1984), Japan (Usami 1979) and China (Lee et al. 1976).

Historical earthquake information for South Africa (SA) is presently available from the Council for Geoscience (CGS) which data has been compiled from various sources such as journal entries, reports, letters, newspapers and international datacentres. This contribution presents the results of a study of available sources in order to determine locations of historical earthquake sources for the KwaZulu-Natal (KZN) province that may not have otherwise been captured in the national and international catalogues. Knowledge of these earthquakes or even their epicentres is an integral part of seismotectonic investigations, which delineate between different earthquake sources for a given region.

2.2 Literature Review

The earthquake record for SA can be separated into an instrumental period (post 1970) and a historical (pre 1970) period which have varying degrees of completeness (Saunders et al. 2008). The first comprehensive historical catalogue was compiled by Fernandez and Guzman (1979). Their study was based on earlier works by Theron (1974), Krige and Maree (1948), Finsen (1950) and De Klerk and Read (1988). Brandt et al. (2005) updated the work of Fernandez and Guzman (1979) by assessing the original journal entries and newspaper articles published in earlier works. Earthquake data from the International Seismological Centre (ISC) and African data centers like Bulawayo (BUL) were added to the national historical earthquake dataset. Von Veh (1988) completed a comprehensive study for the KZN coastal region as part of Eskom's proposed siting of a nuclear power station near Salt Rock. In that study 33 new events were found that had not been included in the national catalogues.

Singh and Hattingh (2008) compiled an atlas of isoseismal maps for SA from 1932. Midzi et al (2013) completed a similar study providing an atlas of intensity data points (IDPs) for the region. Midzi et al (2013) and Singh and Hattingh (2008) used data sources such as questionnaires, newspaper reports and other studies to characterise the events. All of the relevant events have since been incorporated in the CGS catalogue.

Historical earthquake investigations can be expensive and time consuming. Investigations also involve an understanding of the geopolitical setting at the time and the population movements. Resources that have been found worth studying for historical accounts of earthquakes include diaries and letters of the early inhabitants of the region. The first records that might contain datable earthquake references are from about 1500, in the form of diaries and letters of explorers, travelers and laborers. However these resources have not yet been studied for records of large earthquakes. Von Veh (1988) only looked at newspaper records and responses from the general public.

The KZN coastal areas have experienced several potentially damaging earthquakes historically, albeit they occurred at a time when it was less populated and urbanised, hence there is very little memory or record of earthquake damage. Figure 2.1 shows the distribution of isoseismal maps (curves delineating areas with different seismic intensities) in Modified Mercalli (MM) scale of Richter (1958). Potentially damaging intensities to infrastructure start from MM Intensity IV upwards. Historical reports of damage to the KZN coastal areas were reported since 1932. These earthquakes were reported to originate from various sources including St Lucia, Port Elizabeth, Matatiele and even neighbouring countries like Mozambique and Swaziland. The damage reported was significantly less than if there were to be a repeat of the same earthquake today, due to the greater modern infrastructure. Another important factor affecting earthquake damage is that some regions in KZN are situated on thick sedimentary cover so one may find that at a given site the earthquake effects are much greater because of the signal amplification. (Fernandez and Brandt 2000, Midzi et al. 2013, Albin et al. 2014).

The offshore area has many reports of historical earthquake activity. Hartnady et al. (2013) pointed out a number of historical earthquakes in the Natal Valley that aligned along the boundary between the Nubian (NU) and Lwandle (LW) microplates, namely those of 1 November 1942, 22 January 1972, 1 December 2009 and 21 May 1850. The source for the 1850 event documented by De Klerk and Read (1988) and re-interpreted by Albin et al. (2014) was suggested by Hartnady et al. (2013) to be offshore with a magnitude of Mw 8 and located along the NU-LW plate boundary. Ben-Avraham (1998) and Reznikov et al. (2005) reported neotectonic activity (in the Quaternary) from observations of data acquired from marine geophysical surveys. They found young intrusives in the southern Mozambique rift, fractures disturbing the seafloor along the Agulhas Fracture Zone, and young intrusives in the Natal Valley. Goedhart (2007) reported on quaternary faulting in the Eastern Cape region.

Another issue is that up until today the seismic network coverage for the east coast of SA has been relatively poor. While to date the instrumental record in the catalogue is complete for events above magnitude 3, one still needs to be able to detect the smaller earthquakes that occur in the region in order to identify seismic sources for seismic hazard investigations.

Seismotectonic investigations for the country were first published in specialist reports for the CGS for siting of nuclear power plants but these reports were not made publicly available. Andreoli et al (1996) did a comprehensive neotectonic study for the country. Bird et al (2006) modelled stress patterns for Southern Africa. Singh et al (2009) performed a regional study that incorporated both historical and instrumental earthquakes and other multidisciplinary datasets from shallow and deep geophysics, neotectonics and stress fields to delineate source zones for SA. While this was a regional study and only existing datasets were compiled (albeit the datasets were quite sparse and incomplete), Singh et al. (2014) are working on a more localized study that focuses on the KZN region. While several datasets have since been collected and improved (Saunders and Botshielo 2013) this study is an important step in developing a more complete and high resolution geodatabase for Seismic Hazard (SH) investigations.

2.3 Methodology

The first step in the methodology was to collect existing historical datasets for the country. Thereafter a literature review was conducted to find sources of historical earthquake information particularly for the KZN region. Notices were placed outside municipal centers. Due to time constraints these notices were placed randomly in areas within 50km of the Durban city centre. Letters were written to editors of local newspapers soliciting earthquake information from the public.

The information gathered and public responses was compiled and analysed to determine the essential parameters required for the historical catalogue. This compilation was then checked entry by entry to see if any events had been registered in the national datasets. In order to maintain uniformity in the datasets the descriptive information provided on the described damage was converted into the MM Richter Intensity scale.

A list was then made of those events that were not registered in the national datasets. At this stage these events were just Intensity Data points and not locations of earthquake origins (epicenters). The intensity data points (IDPs) have several uses for Seismic Hazard Assessment (SHA) (attenuation, site effect, and vulnerability) but for seismotectonic investigations knowing the epicenter of an earthquake is of paramount importance.

The best methods to determine the epicenters or source or fault parameters of historical earthquakes are those described by Musson (2009) and by Gasperini et al. (1999) however these methods need several observations of a particular event. At this stage of data gathering there was mostly a single observation per event which provided merely the possible geographic location of the source. Note that

the geological setting and framework was not discussed at this stage because the dataset was also too sparse to warrant conclusions on active faults.

To determine possible sources for these events the national and international catalogues were searched. Events that occurred in the same month (i.e. within about 10 days before or after the event) were extracted and then plotted with the IDP of that event. Criteria that could be used to determine the likely source were: 1) clusters of large events, 2) events that occurred in the same vicinity of the sources mentioned above or 3) events which occurred close to the IDP date.

2.4 Results and Discussion

A few key publications were found that provided additional historical data. These were Von Veh (1988), Singh and Hattingh (2008) and Midzi et al.(2013). Responses to letters written to the Berea Mail and the Northglen News in 2013 soliciting information also provided information on some tremors that were felt in the 1950s. In these accounts only the year of events was provided by residents and not their exact dates. Each entry was individually analysed. Most of the events listed in the above publications had been already registered in the database. Those events not registered and that had MMI of IV and greater are listed in Table 2.1, indicating these intensities that are of concern when dealing with ground motion and damage, all of which come from Von Veh's (1988) database. Note that one of the reasons that these events were not incorporated in the national database was that Von Veh's (1988) work was not published.

The entries from the Von Veh (1988) compilation could only be incorporated as intensity data points (IDP) because only a few observations of a particular tremor were made. The exact location of the epicenter of the earthquake should be further investigated. Two larger events of note that were recorded in Von Veh's (1988) catalogue included one that rocked Umhlanga on 17 August 1981 with an intensity V at about 10-30 pm followed by 2 tremors 13 minutes later that lasted 30 seconds each (Natal Mercury, 18 August 1981). The other was in 1944 that was felt in Scottsville (NW-SE shaking) with an observed crack in the ground in Pietermaritzburg. Note that all material used for this study has been preserved in the seismotectonic reference database and geo-database should further investigation be required.

The question then arises, what could be the sources of these large events? The answer might be critical for seismic hazard assessment. On looking at Figure 1, it appears that multiple sources around the region area are capable of generating intensities of IV and V within it. The ISC and CGS catalogues were correlated to the database for events that occurred in the same time period (a few days before or after the event) (see Table 2.2 and Figure 2.2) in order to suggest possible sources of the events listed

in Table 2.1. It's conceivable that there could be an analyst error in the dates of either sources. The likely source could be attributed to 1) regions that have had a high level of activity for that time period or 2) events that occurred in the vicinity of the IDP location around that time period and 3) events that occurred close to the recorded date.

For the event of 8 March 1927, Finsen (1950) reported an earthquake in Mtubatuba (near the location of the 1932 St Lucia event) which is the most likely location for the epicentre of this IDP.

For the event of 26 August 1944 reported from Scottsville, during that month there were a few earthquake reports from all over the country. An earthquake occurred in Beaufort West on the 28 August (Krige and Maree, 1948) which could be a possible source location. Note however that this event was of small magnitude and the supposed epicentre is also located quite far from Scottsville.

For the event of 23 November 1964, no other reports of local earthquakes were found for that time. The only earthquakes reported were in the central MidAtlantic Ridge which is too far to have any effect in the KZN coastal area.

For the event of 1 September 1970, three earthquakes were reported in the Mozambique Channel which is the most likely location of the epicentre of this IDP.

For the event of 13th July 1978, within a few days of this tremor, earthquakes occurred in the Far West Rand (FWR) mining region, Phalaborwa and the East Rand Mining District. However these tremors were of relatively small magnitude and should there have been a large event in the mining region on the 13th July that would probably have been detected.

For the event of 17th August 1981, several small events of magnitude 2-3 were reported in the gold mining areas for that time (not shown in Table 2.2). Other notable events on the same day were in the offshore region and Madagascar. There was also an earthquake in the South Sandwich Islands region (SSI) region which is too far away to have been felt in Natal.

Subsequently all of the events in question were interrogated in the CGS database to check whether they were possibly detected and mis-located but no new information could be found about these locations (Ian Saunders, pers comm.). A detailed report of these findings will be published in further work.

In summary the previously undocumented sources which can most likely effect the region and which might be reliable enough to be considered at this stage is the one in the Mozambique channel (cluster of events in 1970). The SSI source comes up several times and it is postulated that earthquake occurrence there has triggered faulting along the ridge up to the eastern coastline and the Mozambique Channel. This is supported by evidence of an earthquake that occurred in August of 1970 followed by

three earthquakes in the Mozambique Channel in September of that year. Earthquakes might then be occurring on faults near the coastline which are not being detected by the national network. The Mtubatuba source is well known as this is where the 1932 earthquake originated. Note that that this tectonic region marks the path that was taken when the Falklands Islands broke away from Africa 175-125 million years ago along the Aghulhas Transform Fault.

2.5 Conclusions

This study provided insight into possible earthquake sources that could affect the KZN region from freshly revealed historical earthquake data.

The most significant source that should be accounted for in seismotectonic investigations is that of the Mozambique Channel.

Currently the earthquake network coverage for the east coast is rather poor and hence any offshore earthquakes are not being recorded with sufficient completeness. This is a real problem because it seems that some tremors that are being felt in the region (along the coastline) are originating from offshore sources.

While a large portion of this compilation consisted of IDPs rather than locations of earthquake epicentres, a foundation is made for future research in this field that might search historical documents for the epicentres of these IDPs. The epicentres of these events should be located by surveying the public, newspapers and other historical documents.

One should also acknowledge that the locations of these epicentres used in this study also carries some uncertainty (some 50km) for varying reasons (insufficient station coverage and few historical documents to provide good locations). The assessment of this uncertainty is beyond the scope of this study.

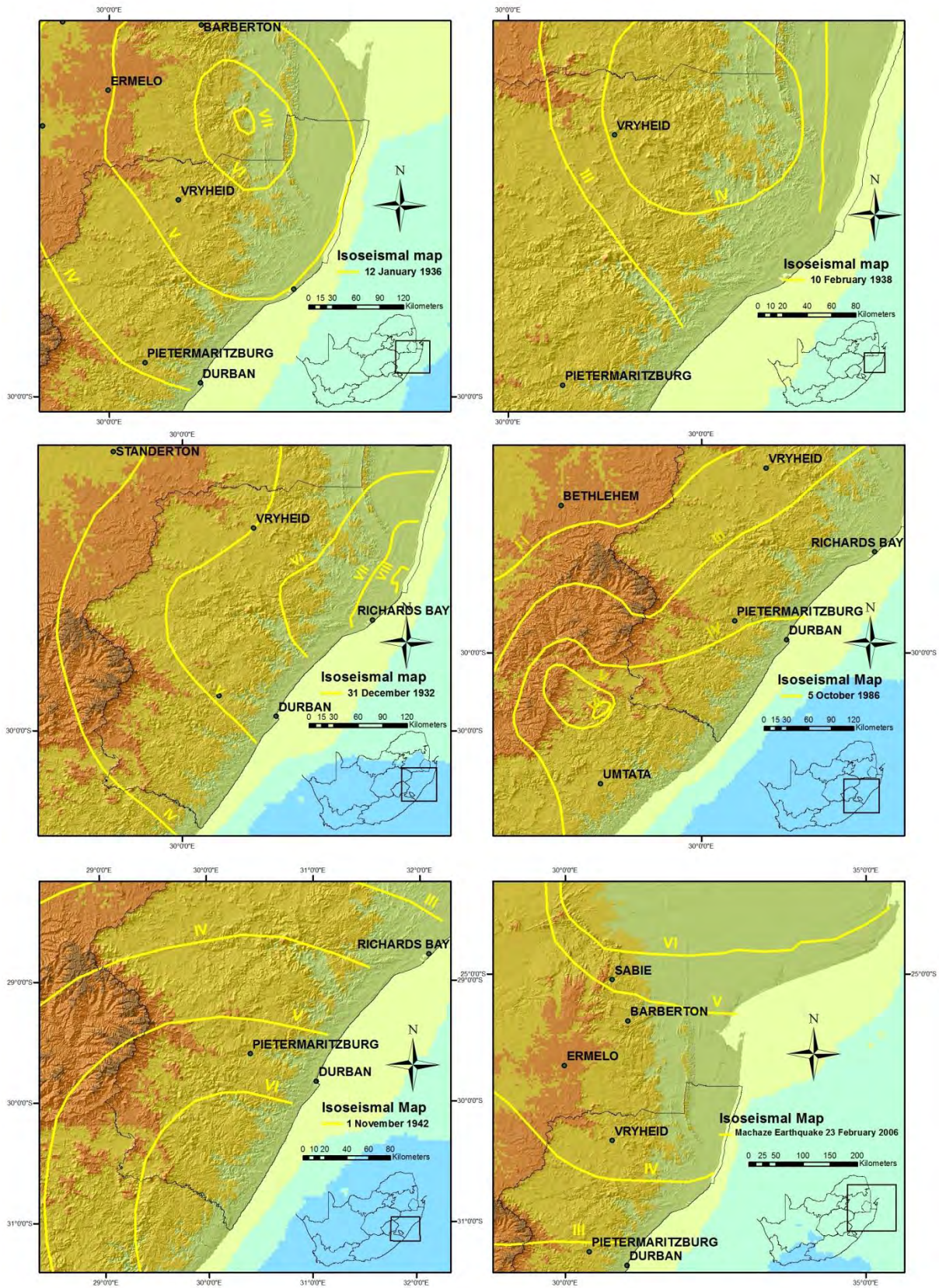


Figure 2.1 Isoseismal maps of significant earthquakes that have occurred within the province (from Singh and Hattingh 2008)

Table 2.1 Listing of unregistered historical events (IDPs) found in this study that is not included in the national historical database

No	Year	Month	Day	Hour	Min	Latitude	Longitude	MM 56 Intensity	Source	Original Source	Affected Town Name	Effects on things
IDP-01	1927	3	8	6	10	-28.1	31.5	IV	Von Veh	Natal Mercury (16/03/1927)	Empangeni	Pictures on wall shook, articles shook and fell
IDP-02	1933	1	3	2	14	-30.1	30	IV	Von Veh	Natal Advertiser 03/02/1933	Ixopo	Rooms vibrated, glasses shook on shelves, windows rattled, bed swayed
IDP-03	1944	8	26	22	0	-29.6	30.3	V	Von Veh	Daily News 26/08/1944	Scottsville	Crack in ground at Pietermaritzburg
IDP-04	1964	11	23	22	10	-29.9	31	IV	Public Accounts	Daily News 24/11/196	Durban	Bed shook, walls and wardrobe swayed
IDP-05	1970	9	1	11	30	-29.8	31	IV	Public Accounts	Daily News 1/09/1970	Durban	Building shook, furniture and machinery vibrated
IDP-06	1978	7	13	8	15	-30.1	30.4	IV	Von Veh	Daily News 14/07/1978	Oribi Flats	Walls moved, bedroom and kitchen furniture shook, window panes rattled
IDP-07	1981	8	17	22	30	-29.7	31	V	Von Veh	N.Mercury 18/08/1981	Umhlanga	Homes shook, Rattling windows, ornaments fell over

Table 2.2 Listing of earthquake events that occurred within the date nearest to the reported tremor [the abbreviated source catalogues refer to FIN – Finsen, MEND – Mendez, KRIG – Krige, ISC – International Seismological Centre, BULA – Bulawayo, PRE – Council for Geoscience)

Event Match	Year	Month	Day	Latitude	Longitude	Local Magnitude	Source	Nearest town	Comment on source location
1927, 3, 8 IV Empangeni	1927	3	10	-28.4	32.3	3.7	FIN	Mtubatuba, KZN	Likely source location – closest date
	1927	3	18	-27	30.8	3	FIN	Piet Retief District, Transkei	Unlikely source location -date
1944 8 26 V Scottsville	1944	8	17	-20.5	32.8	4.3	MEND	Espungabera, Mozambique	Unlikely source location -date
	1944	8	28	-32.5	22.5	3	KRIG	Beaufort West, Cape Prov	Unlikely source location – too far
	1944	9	17	-27.6	30.8	4.3	KRIG	Vryheid, Natal, SA	Unlikely source location -date
	1944	11	12	-29	27.7	4.3	KRIG	Ladybrand, SA-Lesotho Border	Unlikely source location -date
1964 11 23 IV	1964	11	16	-56.06	-27.4	5.24	ISC	South Sandwich Islands Region	Unlikely source location – too far

Durban	1964	11	17	-55.46	-27.9	5.29	ISC	South Sandwich Islands Region	Unlikely source location – too far
	1964	11	20	-0.18	-18.21	5.37	ISC	Central Mid-Atlantic Ridge	Unlikely source location – too far
	1964	11	23	-56	-27.4	5.46	ISC	South Sandwich Islands Region	Unlikely source location – too far
	1964	11	29	-55.32	-25.7	5.37	ISC	South Sandwich Islands Region	Unlikely source location – too far
1970 9 1 IV Durban	1970	8	3	-56.21	-27.23	5.33	ISC	South Sandwich Islands Region	Unlikely source location – too far
	1970	9	1	-23.3	37.6	3	BULA	Mozambique Channel	Likely source location – closest date
	1970	9	1	-23.5	37.6	3.3	BULA	Mozambique Channel	Likely source location – closest date
	1970	9	1	-23.5	37.5	3.4	BULA	Mozambique Channel	Likely source location – closest date
	1970	9	1	-1.8	-12.4	5.12	ISC	North of Ascension Island	Unlikely source location – too far
	1970	9	1	-1.64	-12.68	5.12	ISC	North of Ascension Island	Unlikely source location – too far
	1970	9	1	-1.64	-12.77	5.37	ISC	North of Ascension Island	Unlikely source location – too far
1978 7 13 IV Oribi Flats	1978	7	12	-26.4	27.4	3.5	PRE	Far West Rand gold mines, SA	Likely source location – closest date
	1978	7	12	-26.5	27.6	3.1	PRE	Far West Rand gold mines,	Likely source location – closest date

								SA	
	1978	7	17	-24.3	31.3	3.8	PRE	Phalaborwa Eastern Transvaal	Unlikely source location -date
	1978	7	17	-26.4	27.3	3.7	PRE	Far West Rand gold mines, SA	Unlikely source location -date
	1978	7	18	-26.4	27.4	3.4	PRE	Far West Rand gold mines, SA	Unlikely source location -date
	1978	7	19	-26.5	27.5	3	PRE	Far West Rand gold mines, SA	Unlikely source location -date
	1978	7	20	-26.2	28.2	3.1	PRE	East Rand gold mines, SA.	Unlikely source location -date
1981 8 17 V Umhlanga	1981	8	14	-16.9	40	4.83	BUL	Offshore N. Mozambique	Unlikely source location
	1981	8	14	-32.5	31.3	5.04	BUL	Offshore SA	Likely source location – proximity to event
	1981	8	17	-59.81	-25.65	5.57	ISC	South Sandwich Islands Region	Unlikely source location – too far
	1981	8	19	-20.6	47.3	4.93	ISC	Madagascar	Unlikely source location – too far

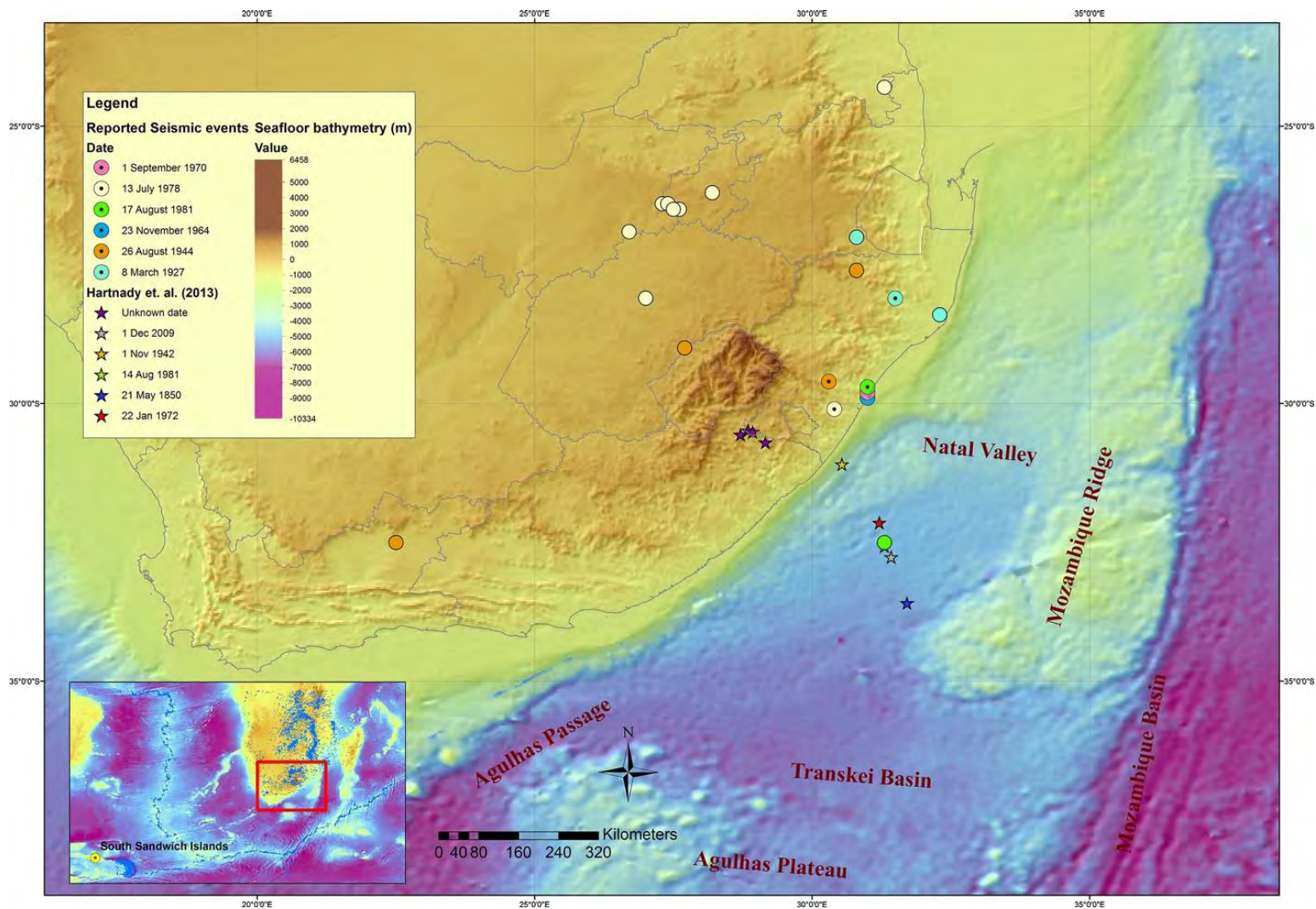


Figure 2.2 Map of southern Africa with seismic events (stars) and IDPs reported in the text (dotted circles) with corresponding earthquake epicentres reported within a few days of the reported IDPs.

2.6 Acknowledgements

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CHAPTER 3: SEISMOTECTONIC ANALYSIS OF KWA-ZULU NATAL, SOUTH AFRICA: DATABASE ASSEMBLY AND AREAL SOURCES INTERPRETATION

The contents in this chapter was submitted for publication and is under review:

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Abstract

A seismotectonic model of the study region is presented from an analysis of earthquakes, structural and kinematic systems. Geo-spatial data from geology, tectonics, regional geophysical anomalies, historical and instrumental seismicity and kinematics are considered.

For what was once considered as a diffuse seismotectonic region with low levels of seismicity and where insufficient, uncertain and incomplete data existed – we now have datasets that are more complete and have higher levels of accuracy.

Earthquake epicentres from both the historical and instrumental record as well as the occurrence of thermal springs correlate with Jurassic faults. An assembly of a variety of datasets and studies are performed followed by a delineation of respective seismotectonic provinces.

Earthquake recurrence parameters were assessed for the seismic provinces. However, many of the provinces had insufficient seismic data to compute parameters. Improved seismic monitoring of the east coast region is required to better characterise the seismic hazard.

Keywords: seismotectonic model, South Africa, seismicity, zonation

3.1 Introduction

The coastal province of KwaZulu-Natal (KZN) is a seismically active region of South Africa (SA) that is the site of large infrastructure developments. The increase in population density and hence vulnerability calls for a thorough analysis of seismic sources and potentially active faults and geological structures.

An areal seismotectonic source model for the province is proposed that is built from a multidisciplinary geo-database that may help in active fault determination and for understanding the causes of earthquake generation. The enhanced earthquake database used in this study contains error ellipses for location and focal mechanism solutions where possible. Fault data was also digitised from historic documents.

The KZN coastal areas have experienced several potentially damaging historical earthquakes at a time with less population density and less buildings, hence there is little memory or record of earthquake damage. Historical reports of damage to the KZN coastal areas have been recorded since 1932. These earthquakes originate from a variety of sources including active zones as far as Mozambique. The damage reported was significantly less than if such events were to occur today, due to the higher level of today's infrastructure and population. The datasets collected reveal that the coastal regions have a number of NE-SW trending faults that originated during the break up of Gondwana. The seismic events correlate well with these faults. Another point of interest is along the Tugela fault where seismic events were recorded. This is also a zone near which a number of thermal springs can be located. The Swaziland region is another potential hotspot from where large earthquakes have originated historically. Thermal springs are also located here indicating a possible region where neo-tectonic activity is taking place.

While seismic hazard maps were calculated for South Africa [Fernandez and du Plessis (1992); Giardini and Basham (1993), Midzi, V., et al. (1999) and Kijko et al. (2003)] in most cases the methodology used for the seismic hazard maps were based on 'zone-free' methods mainly because the seismotectonic model for the region was poorly documented. Internationally, regulations for seismic design of public infrastructure like nuclear power plants, bridges and tunnels, require that seismotectonic models in some form be incorporated in the seismic hazard assessments (SHA) hence its importance. In this work, we analyse all available geological, geomorphological, tectonic, seismicity and geophysical data (from published literature and professional reports of research institutions and surveys) and explain our seismotectonic approach.

3.2 Literature Review – State of the art

Wong et al. (2004) summarised the essential parameters required for a seismic source model. Two types of earthquake sources are required fault sources and areal sources. *Fault sources* are typically modelled as a three dimensional fault surface and details of their behaviour are incorporated into the source characterisation. *Areal sources* are regions where earthquakes appear to occur randomly without any clear association with any of the faults that might be included in the seismic source model.

There are several agreed methodologies for deriving the seismotectonic model [Gonzalez and Skipp (1980), Gasperini et al. (1998), Meletti et al. (2000), Hicks et al. (2000), Le Goff et al. (2011), Terrier et al. (2000); Kumamoto and Masataka (2011); Wheeler et al. 2005, Romeo and Pugliese (2000), Gasparini et al., 1982; Powell et al., 1994; Lavecchia et al., 1994, Costa et al., 1996; De and Kayal, 2003; Nowroozi (1976) and Tavakoli and Ghafory-Ashtiany (1999)]. Best practice for seismotectonic analysis was only recently published in Vilanova et al. (2014). They presented a methodological framework to develop and document the data, assumptions and procedure for zonation. They emphasised the need for the models to be supported by a comprehensive set of metadata. The methodology is also illustrated with a seismotectonic model developed for the Azores-West Iberian region.

Seismotectonic investigations for the country were first published in specialist reports for the Council for Geoscience (CGS) for siting of nuclear power plants, but these reports were not made publicly available. Andreoli et al. (1996) did a comprehensive neotectonic study for South Africa (SA) and Bird et al. (2006) modelled stress patterns for southern Africa including KZN. Singh et al. (2009) performed a regional study that incorporated both historical and instrumental earthquakes and other multidisciplinary datasets from shallow and deep geophysics, neo-tectonics and stress fields to delineate source zones for SA. This was a regional study and only existing datasets was compiled (albeit the datasets were quite sparse and incomplete), While several datasets have since been collected and improved, this study is an important step in developing a more complete and high-resolution geodatabase for seismic hazard (SH) investigations.

Further, Madi and Zhao (2013) integrated several other important datasets in order to investigate the potential for groundwater access on a regional scale in SA. Meghraoui (2015) is preparing a seismotectonic map for Africa and Midzi (pers. comm, 2014) is contributing to this project by providing an investigation of potentially active faults for the SA region. Bommer et al. (2014) published a seismic zonation for the southern part of SA delineating the major craton structures and some coastal and inland faults that may be considered active. This zonation was largely based on earlier works.

3.3 Methodology

The work flow was adopted from studies presented by Terrier et al. (2000), Singh et al. (2009) and elements of the procedure of Meletti et al. (2008). The work flow encompasses four stages: (1) Data collection; (2) Data Preparation for Modelling; (3) Development of Specialist Systems and (4) Compilation of a Seismotectonic model.

The flowchart summarizing the workflow is shown in Figure 3.1. Each stage in itself is extensive. Step 1 involves the collection of multidisciplinary data namely earthquake catalogues; geological maps and faults, geophysical data, GPS data, neo-tectonic and crustal stress data. Ideally one should collect the digital data and preserve all the source information and characteristics of how the data was collected along with its associated errors. In step 2 the data should be prepared for modelling or integration with the other datasets which essentially means that the data should be digitised where possible while preserving the data characteristics as metadata. In step 3 the data can then be organised according to relevance to the three specialist systems (Seismic, Structural and Kinematic). Stage 3 also provides a convenient way to isolate the many complex systems that describe the tectonic forces that contribute to earthquake activity in the region. In step 4 the seismic source zones are created by observing correlations with seismicity and mapped structures and delineating different active tectonic environments.

A comprehensive geo-database has been created which contains all the original reports, shape-files and maps. This database can be revisited when re-testing or updating of the model is required.

The multi-disciplinary dataset collected currently ranges from raw data, first order to advanced models, theories derived from multi-disciplinary considerations and ad-hoc observations on a certain phenomenon. One of the bigger challenges in the data collection is separating the raw data from the analysis and interpretations.

3.4 Data Assembly and Interpretation

The analysis of the individual systems (seismic, structure and kinematic) is presented. Where required, the data collection and preparation is covered when describing each system. Depending on the data available one can create specialist systems like a seismic system (using the seismic data), a structural system (using geological and geophysical data) and a kinematic system using GPS motion vectors and plate boundaries generated from kinematic data. While the seismic and structural models help to conceptualize the historical development and current stressors within the tectonic plate, the kinematic model provides the current dynamic motion of the tectonic plate.

3.4.1 Seismic System

The Council for Geoscience provided historical (pre-1970) and instrumental catalogues of seismic events for the KZN province (Saunders and Botshielo (2013)). Presently the seismic stations are sparsely distributed. The threshold of earthquake sensitivity is magnitude 3. Because of incomplete records and uncertain locations, efforts were made to improve the database (Stage 2 of Figure 3.1). Additional historical epicentres and Intensity Data Points (IDP) have been found from various sources (Singh et al., 2014). For recorded events, their location and magnitude were re-assessed and events traceable to coal mining explosions were removed (Saunders and Botshielo, 2013).

The largest earthquake occurred in 1932 of M_L 6.3 in the St Lucia area (reported also as M_s 6.8 in Fonseca et al., 2014). Its effects were well documented in Krige and Venter (1933). This earthquake was located in the sea offshore the Zululand coast. The nearest point on land to the epicenter was Cape St. Lucia, where Modified Mercalli Intensity (MMI) of IX was assigned on the evidence of sand boils and cracks in the surface. However the damage in this area was small possibly because of low population density. In the severely shaken areas, poor-quality houses were severely damaged. From the evidence of its effects, Krige and Venter (1933) argued that this earthquake was probably caused by slip along a fault in the sea striking in a SSW-NNE direction parallel to the coast. Andreoli (1996) reported on late Pleistocene to Holocene faults that were well exposed near Richards Bay extending northwards through the St Lucia Lakes and the northern KZN coastal plain to Mozambique. These faults should be characterised further in order to better understand the seismicity in that area.

Looking at the spatial distribution of the earthquakes (Figure 3.2) an almost linear band of about 100 km extent exists of both historical and instrumental earthquakes trending in a NE-SW direction parallel to the coast (Figure 3.3). There still exists a concentration of earthquake epicentres in the northwestern region that can mostly be attributed to tectonic activity. The historical and instrumental dataset has slightly different trends as shown in Figure 3.3 mainly due to the fact that historically settlements were more concentrated towards the coastline and hence there were more reports of earthquakes having being felt in these locations.

3.4.2 Structural Systems

The structural system can be organised in terms of shallow structures and deep structures. Shallow structures data are derived from structural mapping and near-surface geophysics. Deep structures data are obtained from shear wave splitting analysis and tomographic studies.

The local geology and structure followed by offshore findings characterise crustal tectonic studies. Thereafter neo-tectonic features are reviewed followed by a review of stress data. Owing to the long time-scale involved, Table 3.1 maps the chronological sequence of the major geological, structural and geomorphological events that have affected the region. It can be used as an easy reference.

3.4.2.1 Generalised Lithology

The lithological units outcropping in the province are shown in Figure 3.4. Whitmore et al. (1999) provided a generalized summary of the rock units outcropping into the province. The rocks in the region are of Archean (2700Ma) to Cenozoic (65Ma –recent) in age. The basement rock units outcrop in the northern part of the province towards the Swaziland border. On the eastern coastline, the Cenozoic Zululand Group silt and sandstone and unconsolidated sediments can be found. Most of the central part of the province consists of the Paleozoic to Mesozoic (300-180Ma) Karoo Supergroup (KS) sediments. The younger Proterozoic rocks (2500-490 Ma) of the Natal Group Sandstone (NGS) and the Natal Metamorphic Province (NMP) can be found outcropping in a NE band between Durban and Pietermaritzburg. From Pietermaritzburg up to Lesotho in a westerly direction, rock outcrops of the KS occur.

The incipient break-up of the Gondwana supercontinent 183 Ma formed fractures and planes of weaknesses that acted as conduits for lava and formation of dolerite dykes and sills. After the separation of Africa and Antarctica at about 140 Ma marine sediments of the Cretaceous Zululand Group were deposited in the newly opened Indian Ocean (Whitmore et al. 1999).

Regional geophysics (Figure 3.5 and Figure 3.6) has been used to image the older granite crustal subsurface overlain by the Karoo sediments. Nguuri et al. (2001) found the crustal provinces for the region and the major provinces that underlie the region are the Namaqua Natal Mobile Belt (NNMB) and the KC (Figure 3.7). The rocks in the NNMB provide locally high magnetic signatures. The regional gravity map also maps the high density rock types along the coastline.

Partridge (2010) identified 34 provinces and 12 sub-geomorphic provinces (Figure 3.8). These provinces are generally geographic regions on the earth's surface that are subject to the same erosional parameters and are similar in terms of structure, shape and mineral composition. Essentially they were identified from macro-reaches that were subsequently classified in terms of slope and cross sectional width, sediment storage potential etc. Principal component analysis was used for the data analysis. For the KZN region a regional sub-domain was identified with the Great Escarpment showing prominence. Numerous rivers drain from the escarpment to the coastline. The St Lucia area has a remarkably different province from the broad province identified for KZN region. This is an interesting observation as the largest historical earthquake in the province originated in this region.

3.4.2.2 Tectonic Fabric

The broad structure of the province consists of undisturbed Karoo rocks in the interior of the province *dipping gently westward into the Karoo basin*. Near the coast, areas of these rocks have been depressed and all lithological types appear at sea-level at several localities together with the NGS and the granite. In many cases these coastal exposures have a pronounced *southeasterly or seaward dip* (Maud, 1961).

Major faults mapped in the province are superimposed on the seismic catalogue in Figure 3.9. Hughes (2008), Von Veh (1994) and Maud (1961) described consistent trends in the fault directions in the province. The mapped faults have three distinct orientations: NE-SW coast parallel patterns, arcuate patterns in the south east, and NW-SE coast perpendicular orientations in the north. These distinct groups occur at the interface between the sediments of the KS and the Pongola Supergroup (NW-SE faults) and at the interface between sediments of the KS and the sediments of the NGS and the NMP. A prominent feature within the KS is the E-W fault line referred to as the Tugela fault which occurs at its boundary with the NNMB. Jurassic faulting and tectonism resulted in the seaward tilting and down-faulting of many faulting units. For examples the Mlalazi fault records a down-throw of 4km, the Nembe fault 800m, the Amitikulu fault 1km and the Umvoti fault 250-300m (Figure 3.9).

Hughes (2008) looked specifically at the Durban area and found relative displacement of faults ranging from a few centimeters to tens of meters. Maud (1961) described in detail faults that had displacements of 300m in places. Normal faults are dominant in the Durban area and are consistent with extensional palaeostresses acting at the time of faulting. Dykes intrude along faults zones of preferential movement.

There has been controversy surrounding the model used to explain the structural patterns and topography of the region. King (1982) supported the theory of ‘limited epeirogenic coastwise tilting’. However, Kent (1938) and Maud (1961) supported a model in which normal faulting caused the structural patterns. The north coast is close to the reconstruction of the margins of the Falklands plateau and is part of the second phase of Gondwana break-up. The faulting patterns observed can be explained by early extensional forces in play resulting in the normal listric E-W to NE-SW faults in Northern KZN coast and dextral lateral forces resulting in the NNE-SSW trend strike slip faults in southern KZN and Transkei. In a third interpretation, Hughes (2008) proposed a plume model to explain the different orientations of the joints observed.

Structural domains provide insight to the underlying tectonic forces at play when an earthquake occurs. Von Veh (1994) defined three broad structural domains by analyzing fault, dyke and lineament data (Figure 3.10). These domains were further subdivided based on geological characteristics. In total 9 subdomains were delineated. The strike frequency distribution of faults, dykes and lineaments

were analyzed for each domain. The direction of maximum principal stress that prevailed during the different tectonic events was also provided for each subdomain.

3.4.2.3 Offshore Region

The Mozambique Plateau and the Agulhus Plateau are well defined and separated by the Transkei Basin (Figure 3.11). The Falkland-Aghulhus Fracture Zone can be found adjacent to the coastline and records the southerly movement of the Falklands islands some 133Ma years ago.

Marine geological investigations (NECSA, 1989) looked at the continental shelf geology from Durban to Richards Bay. The general geology can be described by seaward dipping strata overlain unconformably by Pleistocene aeolite cordons and Holocene sediments. The geology of the shelf edge is characterized by slump facies with compressional features like folds, thrusts and chaotic bedding. Little evidence of tectonic instability was detected. However, just off Durnford and Richards Bay some faults were detected on seismic profiles but the data points were too sparse to make correlations. Normal faults with seaward throws showed submarine slumping off the Zululand coast and some evidence for faulting offshore. Still further detailed investigation is required.

Leinweber and Jokat (2011) undertook a detailed geophysical study of the geology of the Northern Natal Valley and The Mozambique ridge. The Mozambique ridge was formed in a mid-oceanic setting (MOR) and so was interpreted as being one continuous geological structure with the northern part of the Natal Valley.

Cawthra and Uken (2012) undertook a detailed investigation of the evolution of the Durban Bluff and the adjacent Blood Reef and described the region as a storm-dominated broad passive shelf. There were no disturbances of quarternary sediments from studies of seismic profiling.

Green *et al.* (2007) studied the geomorphological features north of the St Lucia area. They particularly looked at the evolution of the canyons at specific study areas. Although their focus was not aimed towards understanding the seismic activity this data can be essential to supplement studies of recent faulting in the area.

3.4.2.4 Neotectonics including offshore neotectonics

Andreoli *et al.* (1996) reported some interesting neo-tectonic observations for SA of which those relating to the KZN region will be summarized here because of their relevance to the study area (Figure 3.9). The seismic catalogue used at the time showed strong correlations with the Amathole-Swaziland Axis. This axis was first identified by Partridge and Maud (1987) as a region of uplift of 800-900m during the Plio-Pleistocene. Along this axis lie a number of thermal springs and spas. From

the seismic patterns they observed an E-W trend from Koffiefontein to Port Shepstone and a NW-SE belt from Richards Bay to Swaziland. Hartnady (1990) proposed a hotspot 'pre-weakening' model to explain the seismicity near Koffiefontein, Lesotho and KZN, arguing that a hotspot moved progressively from Mozambique (ca. 60Ma) through St. Lucia (ca. 10Ma) to Cedarville near Lesotho where it is presently located. He also suggested that this might be the point where the east African rift system (EARS) will extend to in the future. Note that the lack of volcanic eruptions in the Mozambique channel questions the hotspot theory. Another mention of neotectonic activity is that of Southern Natal where McLachlan et al. (1976) reported breccia and distortion of bedding of the early cretaceous conglomerate sandstone at the Egosa fault.

Jackson and Hobday (1980) interpreted deformation of the eolian sands on the top of the Port Durnford formation, as possibly caused by gravity gliding induced by seismic triggering. This could also be interpreted as thrust faults because the area is seismically active. Kruger and Meyer (1988) inferred that a normal fault of down-throw 30m displaced the Uloa and Port Durnford formation in Northern Zululand. This investigation was extended to try to trace the Uloa formation through the resistivity method regionally and several EW trending depressions were found – one near the Port Durnford fire look-out tower. They describe in great details the complex shortening structures in the lignite-bearing beds of the Port Durnford formation (of Holocene age) (NECSA, 1989).

Krige and Venter (1933) reported surface faulting east of Mtubatuba at Shire's mill during the earthquake of 1932. Further south, the Tugela river course is fault controlled which manifests themselves as linears on the satellite imagery and a number of the linears cut through unconsolidated sand (NECSA, 1989).

Further north Ben-Avraham (1995) and Reznikov et al. (2005) reported offshore neo-tectonic activity (in the Quaternary) from observations of data acquired during marine geophysical surveys. They found young intrusives in the southern Mozambique rift and fractures disturbing the seafloor along the Agulhas Fracture Zone, and young intrusives in the Natal Valley. Wiles et al. (2014) found soft sediment deformation in the Mozambique ridge.

3.4.2.5 Stress Field

“Stress regime” refers to the orientation of deformation produced, using an Andersonian classification into normal faulting (NF), strike-slip faulting (SS), and thrust faulting (TF).

Bird et al. (2006) reported normal faulting in the Funhalouro-Mazenga Graben Mozambique. Ferro and Bouman, (1987) and Saunders and Botshielo (2013) reported normal fault and strike slip mechanisms for some earthquake records (Figure 3.2). The fault plane solutions were obtained by

different methods: calculated using the FPFIT algorithm (Reasenberg and Oppenheimer, 1985), and a catalog created using the HASH algorithm that tests mechanism stability relative to seismic velocity model variations and earthquake location (Hardebeck and Shearer, 2002) and Seisan's FOCMEC algorithm (software by GeoSIG).

The World Stress Map, Zoback (1992), Heidbach et al. (2011), provides a database of stress data however none of the data points in that database fall in the study area.

Von Veh (1994) summarised the state of stress for the KZN region and interpreted this for three major structures – Phanerozoic, Proterozoic and Archean. The direction of maximum principal stress for each structure was different due to the particular tectonic phases as summarised in detail in this work.

Bird et al (2006) attempted to identify the most significant feature of the stress field in the southern Africa region, and attempted to reproduce it with finite element neotectonic models to determine its origin. Modelling experiments were conducted with program shells that use a thin shell approximation to model neotectonics of the lithosphere, based on estimated structure and temperatures, estimated rheology, and the conservation of momentum. Elastic strain is neglected, and therefore the velocities and strain rates predicted should be considered as quasi-static long-term averages. Once each model calculation is iterated to convergence, it predicts long-term average surface velocities, anelastic strain rates, fault slip rates, and stresses. The predicted stress regime (actually strain rate regime) is determined by the orientations of the principal strain rate axes giving results in terms of normal faulting (extensional), strike-slip faulting and thrust faulting (compressional).

In the southern Africa region, the highest density moments (a measure of variation of the density vertically in the lithosphere) are in the elevated continental plateaus, so these regions were predicted to spread laterally. Consequently, the continental regions were almost all predicted to be in the NF regime. The strong belt of old oceanic lithosphere just offshore restricted this spreading tendency, and it experienced much higher stress intensities, with primarily SS regime close to the continental margin, and TF regime farther offshore. The predicted fault orientations are NS in the north (St Lucia/Richards Bay/ Mozambique) region and NW-SE towards the South (Bird et al (2006)).

These predictions fit well the fault plane solutions of Saunders and Botshielo (2013) with normal faults striking NW SE in the northern continental region, strike slip in the mountainous Lesotho region and strike-slip at the continental margin (Figure 3.2).

One controversial aspect of Bird et al. (2006) is the projection of the southernmost extent of the EARS. It is located as far as the central KZN (29degrees latitude). The largest earthquake that occurred on the southernmost extent of the rift was in 2006 and had its epicenter in Beira some 1000km away from this extension point (21 degrees latitude). If it were the case that this rift system

extends or will be extended to this point (Bird et al. (2006) rift projection) in the near future it will most probably avoid the much more stable cratonic regions. There is certainly evidence of springs and seismicity along the Swaziland – SA boundary that supports this extension southwards (27 degrees latitude) however there is little evidence of very high seismicity further south (excluding the Tugela fault system – which strikes E-W and has a different suspected mechanism). Singh et al. (2014) noted several ‘larger’ earthquakes (of intensity V) that were undetected by the national network and are believed to originate offshore – which is probably the most likely location for the extension of the rift system.

However extensional structures including normal faults with down-dip lineations and breccias with open space fillings are abundant in the region. . The geometry of the cretaceous faults, tension gashes and veins are consistent with extensional stresses directed approximately perpendicular to the coast (Maud 1961).

3.4.2.6 Mantle Structures

These studies help to identify boundaries of provinces deep within the earth.

Colli et al. (2013) conducted full waveform tomography for the South Atlantic region and this included the Southern African region. From tomographic slices at 100km, 150km and 200km depth, the Precambrian cratons can clearly be distinguished having fast anomalies (4.6-4.8km/s) in contrast to what is seen in the EARS that is characterized by slow velocity anomalies (4km/s). At 250 km depth the anomalies at the cratons are less pronounced and are dominated by slower velocities. At depths between 300km and 450km there is an overall fast mantle (4.7-5km/s). Still the EAR is clearly visible as having a relatively slower anomaly than the rest of the region indicating that there is a large regional mantle plume and a zone with high potential for stress and seismic activity. However the extent of this anomaly stops at the Rovuma-Somalia RO-SOM plate boundary corresponding with the start of the Archaen craton – indicating stability and the absence of hotspots that cause crustal thinning and deformation.

Several geophysical studies were undertaken primarily to understand the nature of the African superswell – an anomaly that shows the African continent at a significantly higher elevation compared to the other continents around the world. These include the study of Nguuri et al. (2001) who focused on defining the crustal structure across the Kaapvaal craton (KC), Limpopo and Zimbabwe craton (ZC) using seismic receiver functions, while the tomography work of James et al. (2001) focused on the deep mantle lithospheric structure. Fouch et al. (2004) produced S- and P- wave velocity perturbation models for depth of 700km and found evidence for the existence of a deep mantle keel

underneath the KC craton. Kgaswane et al. (2009) and Nair et al. (2006) focused on the lower crust 20-30km and found shear wave velocities of $\geq 4\text{km/s}$ for the Achaean and Proterozoic terrains. Khoza et al. (2013) also looked at the KC and ZC boundaries to understand its tectonic framework and noted a collision of these cratons about 2.6 Ga but his study area is further north of the KZN province.

3.4.3 Kinematic System of the African Plate

Kinematic models for East and South Africa were developed by Calais et al. (2006), Stamps et al. (2008) and Fernandez et al. (2013) using geodetic data. Saria (2013) used GPS data to look at the African plate kinematics for the East African Rift System (EARS). The findings for all kinematic models are that the African plate can be subdivided into two major plates– Nubia (NU) and Somalia (SOM) and three sub-plates Victoria (VC), Rovuma (RO) and Lwandle (LW). The NU behaves as a rigid plate with motions at the 0.6mm/yr level. Relatively larger plate motions are observed on the eastern side of the EARS. Larger plate motion rates are observed in the north (Tanzania/Ethiopia of 4-5mm/yr) and lower plate motion rates of 1mm/year are observed in the Mozambique region. These motions have an almost easterly trend. Towards the Southwest Indian Ridge (SWIR) (on the SOM plate) the plate motion changes dramatically to SE and the rate of motion also increases (4mm/yr) Saria (2013). Hartnady et al. (2013) pointed out a number of historical earthquakes in the Natal Valley that aligned along the boundary between the Nubian (NU) and Lwandle (LW) microplates.

Malservisi et al. (2011) analysed GPS data from the South African Trignet network. They found that the cratonic regions in SA are stable with a relatively larger deformation rate in the Cape Town region. They also found deformation possible along the southern coast and along the Mozambique belt. On a broader view the African continent behaves like a rigid plate with motions less than 2mm/year with a clockwise rotation of the South African region with respect to the Nubian region. Data was lacking to confirm some of their hypothesis. Additional geodetic data along with its measures of uncertainty should be acquired and incorporated in some way in the seismotectonic modelling. Uncertainties relating to system, data and application errors should be quantified by the means of implementing multiple datasets in a logic tree application.

Reeves (2013) used fracture patterns from the mid-oceanic ridges to obtain Euler poles of rotation from before the breakup of Gondwana. Large scale regional motions were tracked and predicted. On a large scale- the African plate is colliding with the Eurasian plate at a rate of 2-6mm/year. The Reeves (2009) model is particularly interesting because the reconstruction of the plate motion co-incides with the occurrences of mantle plumes or hotspots that according to 3a theory long proposed by geologists, have given rise to islands like Marion, Bouvet and Tristan da Cunha.

3.4.4 Discussion - Assimilation

Probably the most daunting task of an analyst is to now combine and assimilate these systems and datasets into meaningful information that leads to the best possible classification or zonation model.

One can be guided by the broad tasks set out in Step 4 of Figure 3.1. This section discusses possible fault sources and areal sources based on the datasets provided in the different systems presented in the previous sections.

FAULT SOURCES

Following US NRC guidelines, a “capable fault” is a fault that exhibits one or more of the following characteristics:

- (1) Movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years.
- (2) Macro-seismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.
- (3) A structural relationship to a capable fault according to characteristics (1) or (2) of this paragraph such that movement on one could be reasonably expected to be accompanied by movement on the other.

There are a number of faults located north of the study area that can be linked with seismicity and where detailed investigations of the fault characteristics are required. The seismic system (especially the instrumental seismicity) clearly shows that seismicity is occurring along pre-existing zones of weakness. The potentially active faults are by definition those that are favourably oriented in relation to the stress field in the region. This is also observed in many other settings (see the Korean Peninsula discussed by Hong and Choi, 2012; Choi et al., 2012). The continental-margin environments require dense seismic networks for complete event records.

There are definitely a number of faults within close vicinity of earthquake epicentres however there needs to be further investigations to identify which fault can be attributed to which earthquake. Towards the coastline there are several fault traces. Many faults correlate with both historical and instrumentally recorded earthquakes. While the instrumentally recorded earthquakes have better locations (5km) the uncertainty in locations of the historical events still needs to be assessed. The Tugela fault for one can certainly be considered active along several segments because clearly it can be correlated with seismicity and springs. A strong gravity anomaly also can be seen along this fault.

Note that the pattern of the aeromagnetic signatures correlates well with the fault patterns and would be very useful in identifying major fault trends.

Upon looking at the digital elevation model (DEM) which correlates with linear expressions already indicated by fault lines – it can be seen that fault lineaments in the south of the map continue beneath the KS (Figure 3.9). The fault pattern becomes more complicated in the northern-most part of the region where differently trending faults intersect. Detailed investigation of faulting patterns is required for the region especially beneath the Karoo sediments. Remote sensing techniques can be used in places where there is thick overburden. Detailed seismic monitoring will also help delineate those structures on which earthquake epicentres occur because the faults are located close to each other. In preliminary investigations of fault correlations with seismicity Ngoasheng (2015) provided a map of such faults (see insert in Figure 3.9). In order to characterise any fault for a SHA study one should have the fault trace digitally, its formation age and age of its last movements, the rake, dip and slip rate. Such data still needs to be acquired hence faults were not included further in the zonation. Henceforth only areal zones are considered.

AREAL SOURCES

Several methods are available for the modelling e.g. implementing of the self-organising map (SOM) algorithm of Mojarab et al. (2013) or Principal Component Analysis (PCA) by Kumamoto and Masataka (2011). Alternatively one can also consider a re-assessment of the finite element neotectonic models of Bird et al. (2006) with the revised data. The structural, geomorphological and crustal province boundaries are shown in Figure 3.12. The kinematic boundaries do not affect the study area. The offshore structural boundaries are also available on a regional scale but are not considered here because of the poor seismic coverage offshore. Ngcobo (2015) attempted to classify the combined datasets using the SOM algorithm available in the IDRISSE Selva software. This work is ongoing. There is still much uncertainty as to the weighting required when integrating the boundaries, the incomplete coverage of seismic events and the poorly developed deep earth structural model. In view of these limitations a manual interpretation was selected.

The best rationale for the manual interpretation was provided by the structural domain delineation of Von Veh 1994 (Figure 3.9). The following rationale was considered in adopting the areal seismotectonic provinces which are essentially comprised or derived from Von Veh's (1994) subdomains.

The broad (regional) domains that were preserved in the Von Veh (1994) model are those of the NNMB and the KS suggested by Nguuri et al (2001) and observed by several other datasets (s-wave

velocity, tomography, geology, aeromag, gravity). An important note is that these regional domains are separated by the seismically active Tugela fault that is actually a network of related faults. The Tugela fault is also the location of several springs indicating a likely region for neo-tectonic activity.

The other rationale for the domain and subdomain delineation was the noticeable faulted coastal region and the relatively unfaulted western region. Also there is a noticeable variation in the lithology in the northeastern region (Mtubatuba-Richards Bay- St Lucia).

The structural provinces suggested by Von Veh separates the KZN region into 3 major domains.

- a. Domain 1
- b. Domain 2 and
- c. Domain 3

Domain 1 The KC portion of the region underlain by Archaen granites, gneisses, metavolcanics and metasediments. This domain can be further subdivided by the southern (1a) and (1b) subdomains. 1a lies adjacent to the southern margin of the KC where the earlier Archaen structures are overprinted by later ones related to the Proterozoic Namaqua Natal orogeny.

Domain 2 is the NNMB portion underlain by granites, gneisses, migmatites and metasediments. It can be further subdivided into subdomains (2a) and (2b) where (2a) is the northern thrust front adjacent to the KC and (2b) is the southern Mapumulo Group.

Domain 3 is the portion underlain by the Natal Group and the Karoo sequence. The KC boundary and the belt of highly fractured rock extend some 70km inland from the coast. Subdomain 3a is the faulted region south of the KC and Subdomain 3c is in the north. Subdomains 3c and 3d lie in the relatively unfaulted western region south and north of the KC. Subdomain 3e defines the faulted region overlying the KC. It is bounded by subdomain 3d to the west and undeformed cretaceous and younger sediments to the east.

The zones delineated have various concentrations of seismicity (Figure 3.13). It may not be possible to determine seismic hazard parameters for each zone owing to the lack of seismic data in some zones.

If one were to compare the more detailed interpretations provided in this study with that of Singh et al (2009) one can see that the study area falls within zone 5 where then there was little knowledge of the underlying Gondwana related structures and the large Tugela fault running centre to the study area.

While these interpretations still may not be sufficient for seismic hazard type assessments for critical structures owing to the low resolution of datasets used it can serve as a starting point or

reconnaissance study for these detailed investigations. It should also be used with caution and more attention should be placed in characterising faulting in the region.

For the recurrence parameters one needs to include the recurrence model, recurrence rate – which can be obtained from the slip rate or average recurrence interval for the maximum seismic event, slope of the recurrence curve (b -value), and maximum magnitude as obtained from a completed seismicity catalogue. The main problem here is that the seismicity catalogue is often short (a few tens of years) and incomplete (does not cover all the magnitude spectrum).

Earthquake recurrence parameters are an essential component in SHA. The basic parameters required is the m_{min} , the minimum detection threshold of the network; the upper bound magnitude m_{max} representing the maximum expected magnitude, the Gutenberg- Richter earthquake recurrence parameter b -value and the activity rate λ , which is the annual number of earthquakes above the lower bound magnitude m_{min} . The earthquake recurrence parameters were calculated by Mapuranga and Singh (2015) based on maximum likelihood procedure and results are shown in Table 3.2. Note that only values for Zones 3c and 3d could be assessed as there was not sufficient data to perform a reliable calculation for the other zones.

Note also that these results are comparable with the Singh et al. (2009) study and the Martinez (2015) study for the b values but not for the m_{max} values. The reason being that the maximum observed or recorded magnitude max_{obs} for zones 3c and 3d are $M_L = 5.6$ and $M_L = 4.4$ respectively. The higher magnitudes are coming from zones 3a which have been incorporated in the Singh et al. (2009) and the Martinez (2015) study.

Martinez (2015) performed a seismic risk assessment to calculate the percentage of risk that buildings have of being damaged for the eThekweni Municipality area. The risk was assessed according to twelve structural trait categories available in South Africa and a probabilistic approach was followed. All earthquakes within a radius of 300 km from the Durban area were incorporated and seismic hazard values were calculated based on a methodology that does not require the knowledge of the seismic source zones.

The results from the study are shown in Figure 3.14. The building classes that were found to potentially suffer the highest proportion of damage were Unreinforced Masonry (URM) structures (Building Classes 3, 4 and 5). In the studies done by Pule (2014) and Van der Kolf (2014), it was established as well that unreinforced masonry buildings are usually more vulnerable to seismic damage. In South Africa, URM structures are commonly used and it should be a concern when appropriate design procedures are not followed for such structures. In contrast, the building classes with the lowest annual expected damage percentage (more resistant to damage) were class 12 and 2 (Long Span Buildings and Light Metal Buildings) (Martinez, 2015).

3.5 Conclusions

This research has shown that what was once considered as an intra-plate region with low levels of seismicity, where faults were considered inactive, has actually a moderate level of seismicity. It has been illustrated that more information is available in the earth science dataset than previously known hence a more detailed seismotectonic zonation is possible.

Seismic events can be correlated with the old pre-existing faults (Ngoasheng, 2015). There is certainly a level of reactivation in place and an accumulation of stresses along these structures. Hence there is potential for further site investigations especially on faults identified as potentially active. Many of these faults can be located within the delineated zones. Seismicity is driven by release of stress along pre-existing fractures. Another key dataset that is lacking is that of Quaternary faults and neotectonics. This data might be acquired through LiDAR.

There is also room to improve the historical earthquake dataset. However the instrumental seismic dataset can only be improved by densifying the seismic network. Investigations are required for more computerised methods for investigations – particularly looking at SOM algorithms and clustering (Ngcobo, 2015).

A detailed risk assessment is required following on Martinez (2015) study in order to reassess the risk based now on the newly acquired zones and to better understand the building vulnerability of the province as performed for the Durban CBD (see Tshabalala, 2015) .

Historical datasets on tsunami occurrences are sparse (Kijko et al., 2014 and Cawthra and van Zyl 2015) though they would be pertinent for this kind of study.

Emphasis should also be made on efforts of the CODATA initiatives to encourage data citation practices and open access to data. Initiatives are also underway for training into standards and best practice for data collection which is very important in multidisciplinary studies such as these.

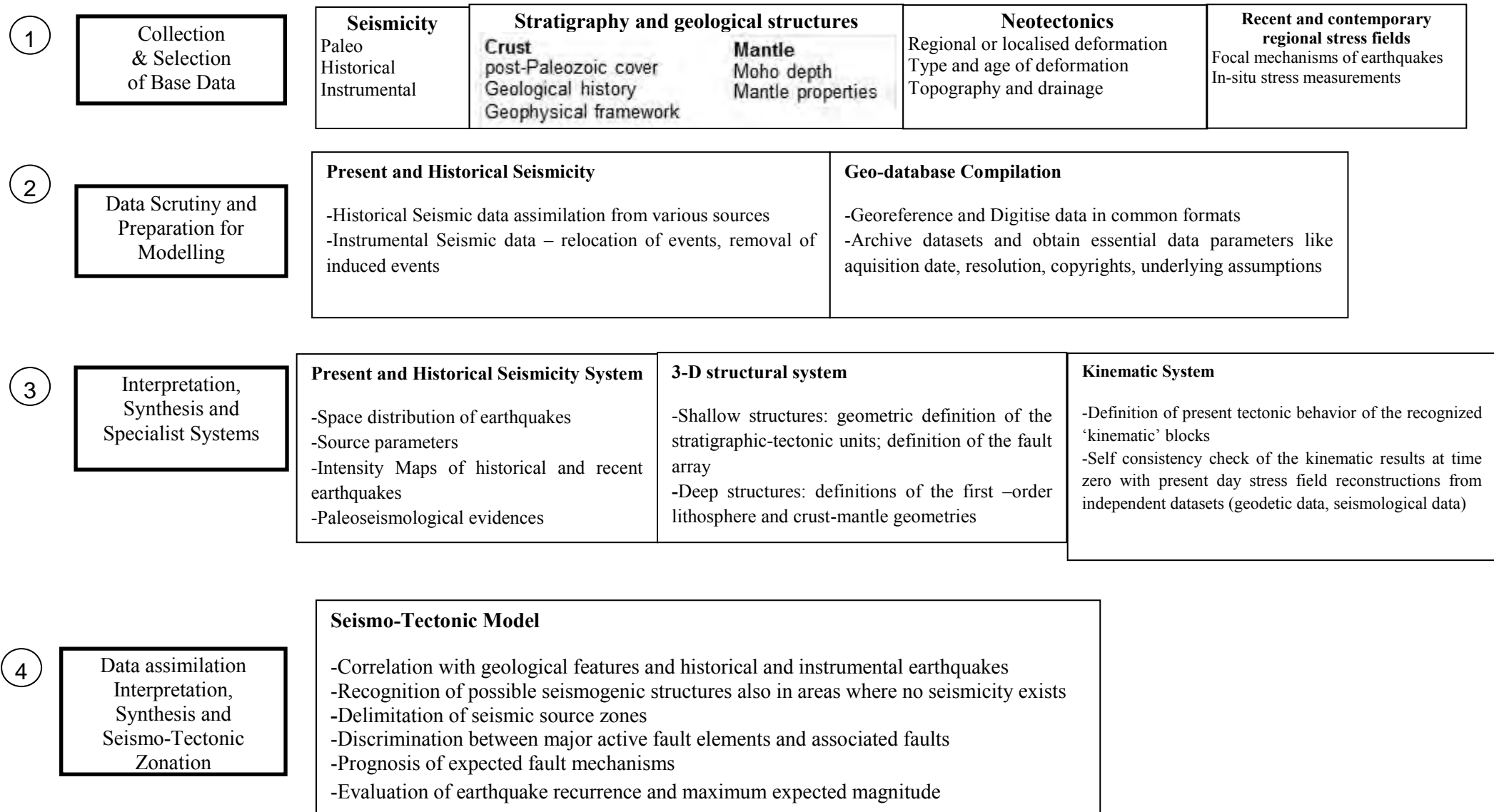


Figure 3.1 Flow chart of scheme for seismo-tectonic modelling

Table 3.1 Regional Geological, Geomorphological and Structural History of the KZN province (Compiled with information from Partridge and Maud 1987 and Whitmore et al 1999)

PRECAMBRIAN 2500-570	PALAEOZOIC 570-250	MESOZOIC 250-65		CENOZOIC 65-0	
		EVENT	GEOMORPHIC MANIFESTATION	EVENT	GEOMORPHIC MANIFESTATION
<p>1000 Ma Natal Metamorphic Province granite and gneiss</p> <p>2700 Ma Pongola granite</p> <p>2900 Ma Pongola Supergroup</p> <p>Nsuze Group sandstone and shale</p> <p>Nsuze Group basalt and sandstone</p> <p>Kaapvaal Craton</p> <p>Granite and greenstone</p>	<p>180-300Ma Karoo Supergroup</p> <p>Lebombo Group rhyolite and basalt</p> <p>Drakensburg Group basalt and dolerite</p> <p>Stormberg group mud and sandstone</p> <p>Group mud and sandstone</p> <p>Ecca Group shale and sandstone</p> <p>Dwyka Group Tillite</p> <p>490 Ma Natal Group Sandstone</p>	<p>Late Jurassic Early Cretaceous-to end of early Miocene – African I Cycle of Erosion</p> <p>Extensive Volcanic activity – seaward tilting and downward faulting along the Natal coast – NNMB and KS rocks lowered to sea-level along the coast</p> <p>125 Ma -98Ma Second Phase of Gondwana break-up.</p> <p>175-125 Ma Antartica/Madagascar broke away from Mozambique/Kenya/Tanzania</p> <p>Late Jurassic Early Cretaceous-Fragmentation of Gondwana [rift-faulting- complex network of faults</p>	<p>Advanced planation above and below GE-development of laterite and silcrete profiles</p> <p>Falklands Islands broke away from Africa along a short rifted margin and moved 1300km along the Agulhus Transform Fault</p> <p>Movement along the extentional transform along the Tanzanian continental margin and the northern end of Lebombo and the southerneastern side of the Falklands island</p> <p>Initiation of the Great Escarpment</p>	<p><65 <i>Zululand Group silt and sandstone</i></p> <p>Late Pliocene to Holocene – Climatic and sea-level fluctuation</p> <p>Late Pliocene to Holocene –Post African II cycle of erosion</p> <p>Late Pliocene (2Ma) – Major Uplift (600-900m)</p> <p>Early Mid Miocene to Late Pliocene – Post African 1 cycle of erosion</p> <p>18 Ma End of early Miocene (18 Ma)- Moderate uplift (150-300m)</p>	<p>Gravity Sliding in Port Durnford Fm</p> <p>Marine benches, coastal dune deposits, river terraces</p> <p>Formation of Post African II surface, incision of gorges, down-cutting and formation of terraces along rivers</p> <p>Asymetrical uplift of subcontinent, major westward tilting of interior land surface, Monoclinial warping along southern and eastern coastal margins</p> <p>Formation of Post African 1 surface</p> <p>Westward tilting of African surface with limited coastal 46onoclonal warping</p>

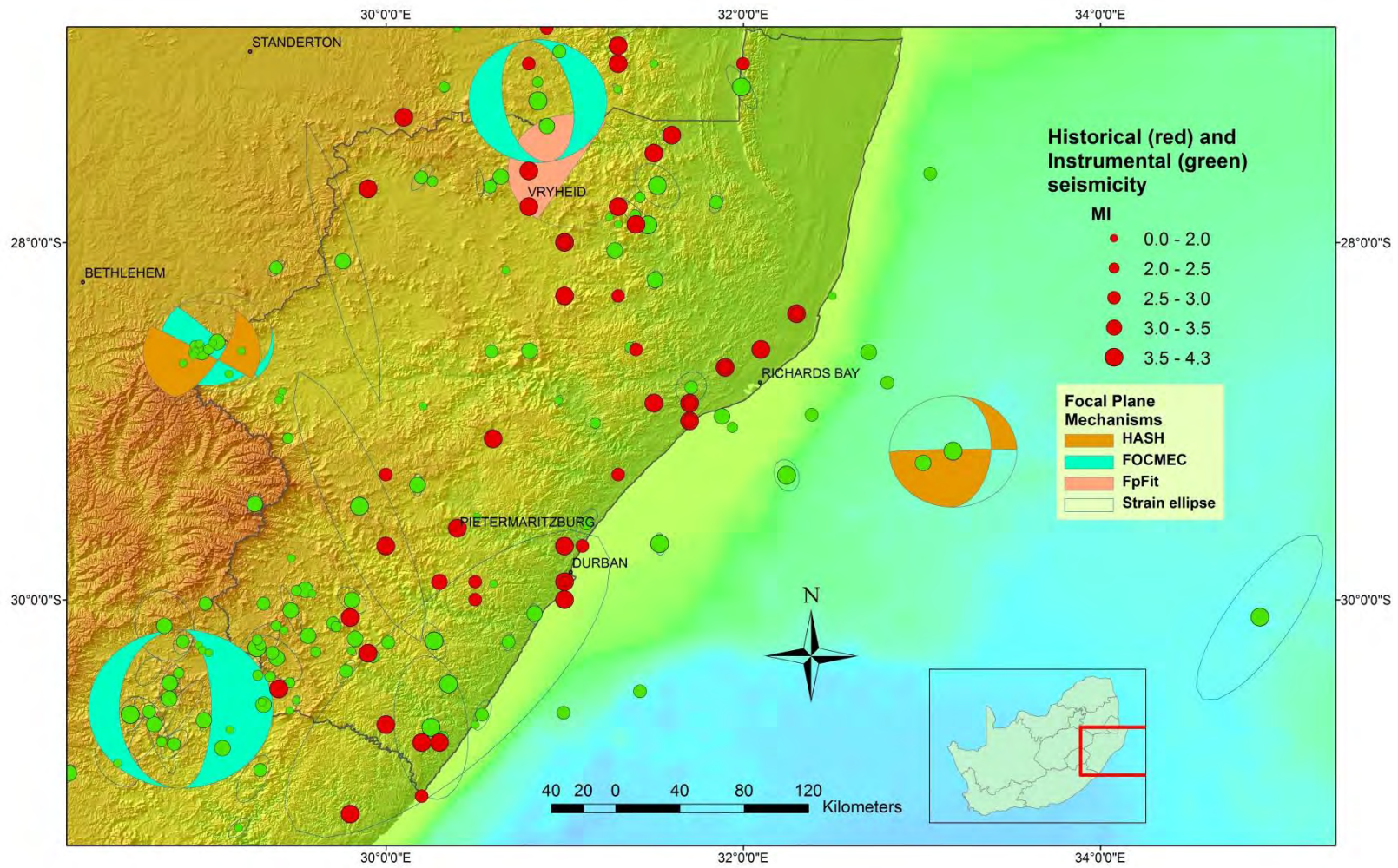


Figure 3.2 Seismicity of the KZN region with results of focal mechanism studies (data from Council for Geoscience)

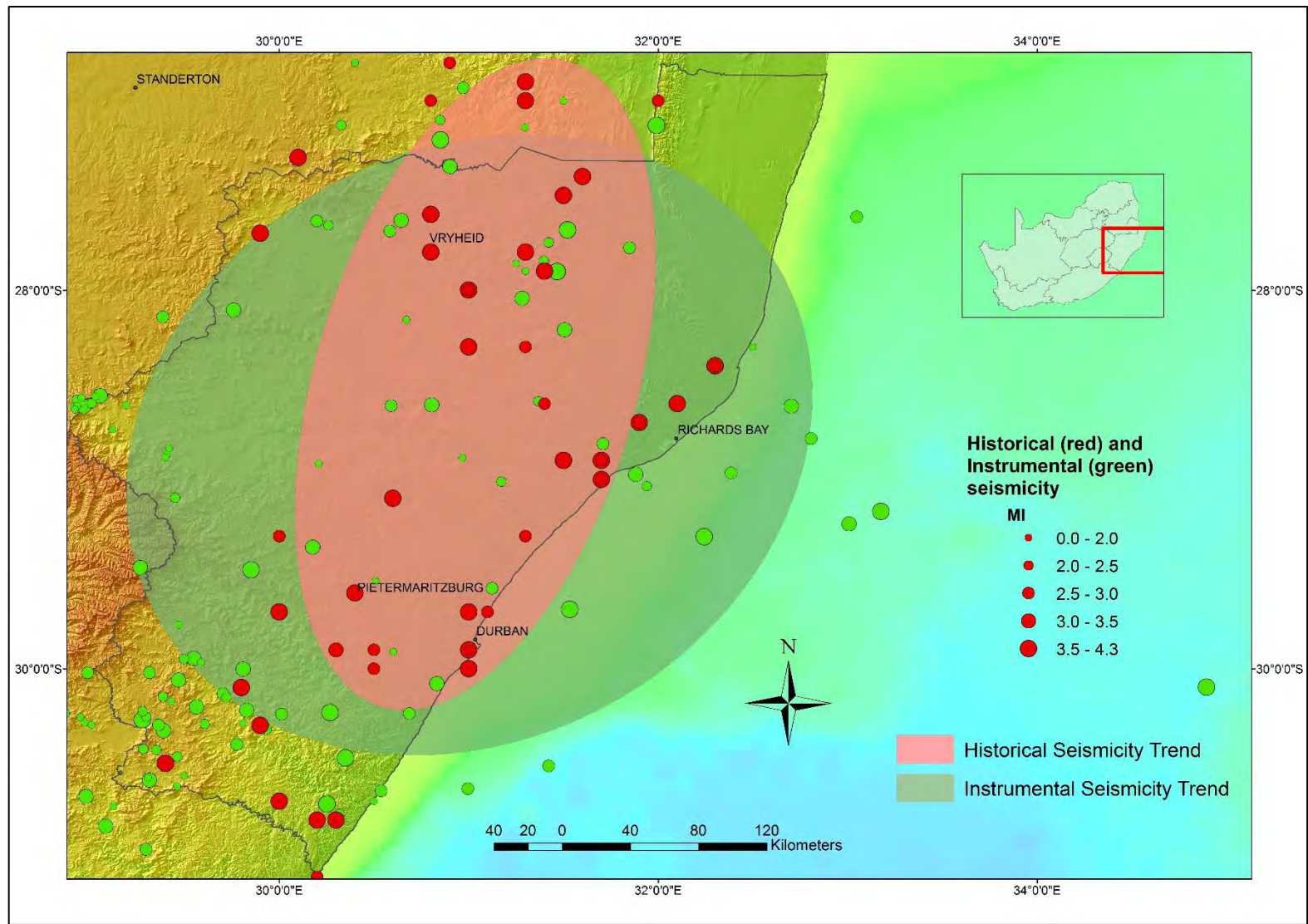


Figure 3.3 Map of Historical and Instrumental Seismicity Trend

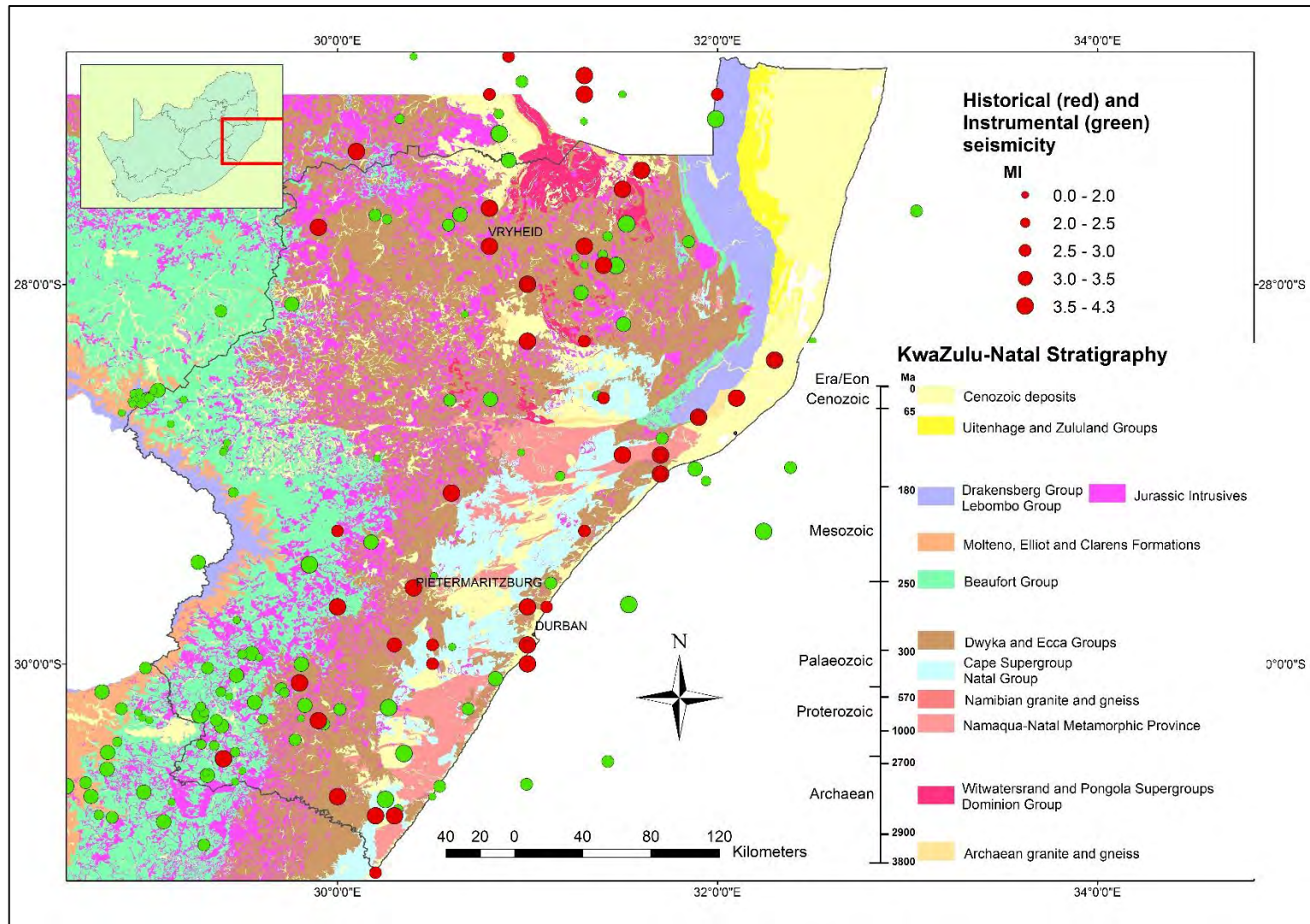


Figure 3.4 Generalised geology of the KZN region at a scale of 1-250K, seismicity is plotted in the background (data from Council for Geoscience)

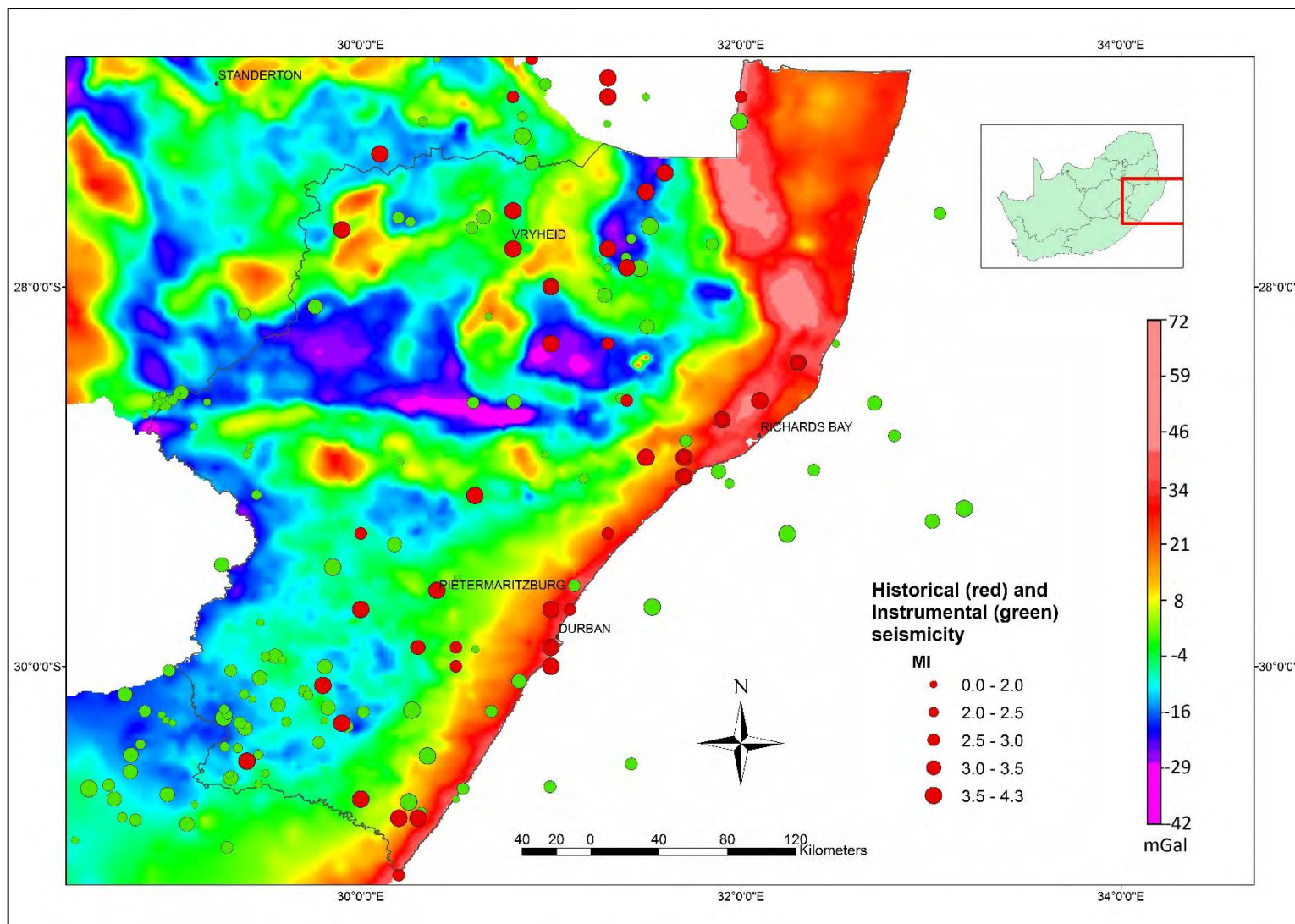


Figure 3.5 Regional gravimetric map of South Africa superimposed on the major geological boundaries and the seismicity. (data from Council for Geoscience)

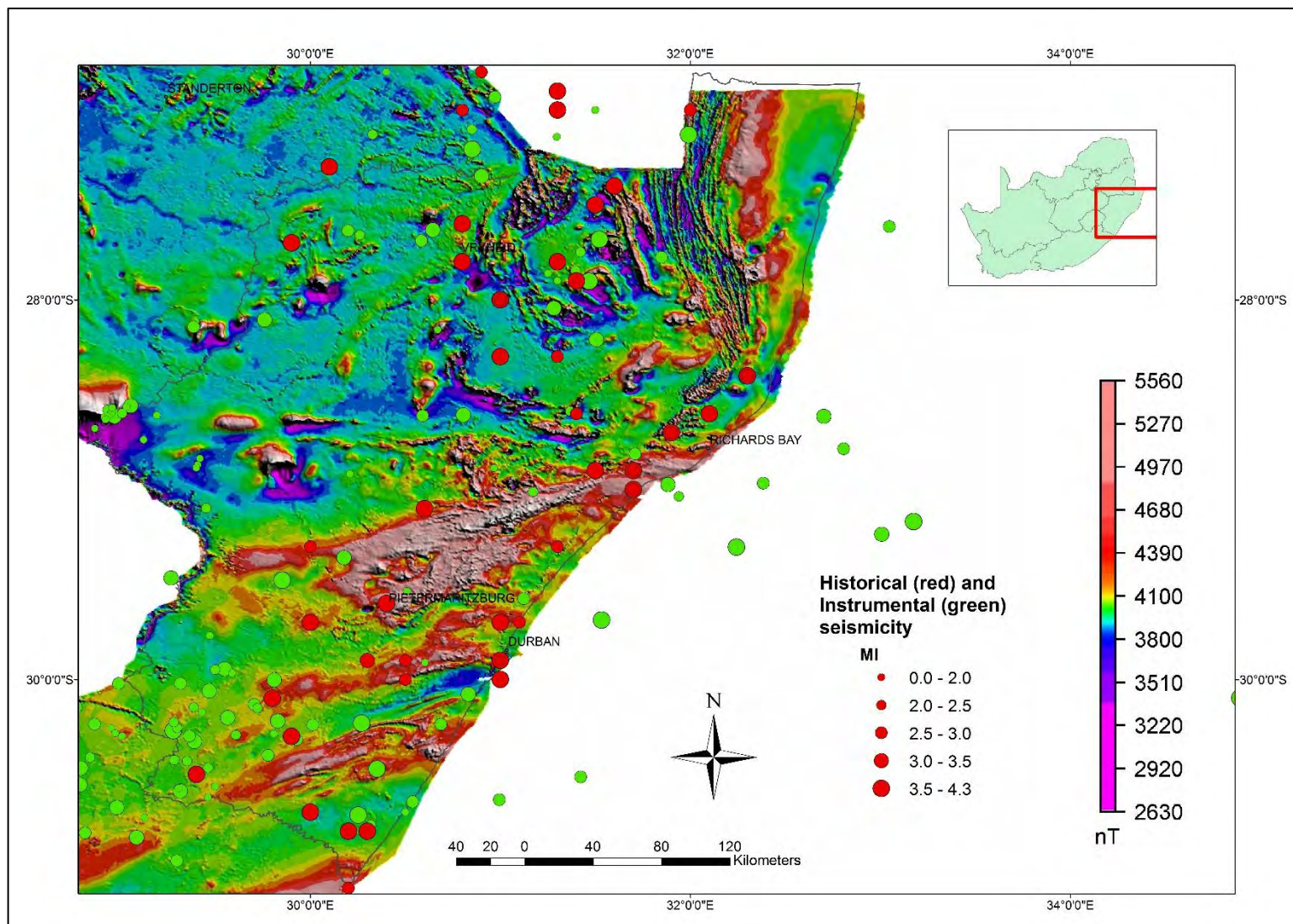


Figure 3.6 Magnetics Regional aeromagnetic map of South Africa superimposed on the seismicity (Data from Council for Geoscience)

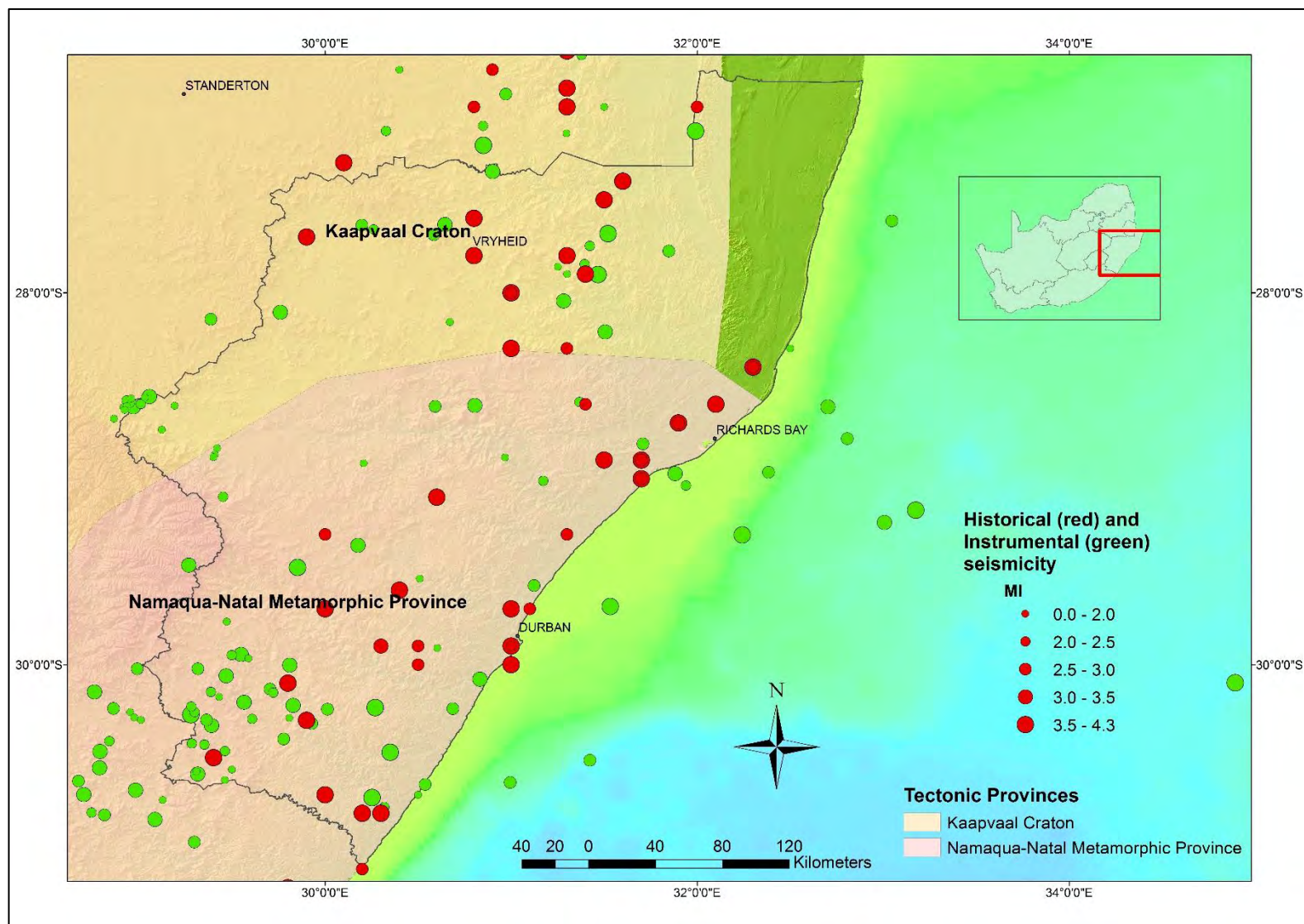


Figure 3.7 Major geological provinces of KZN superimposed with the seismicity (adapted from Nguuri *et al.* 2001)

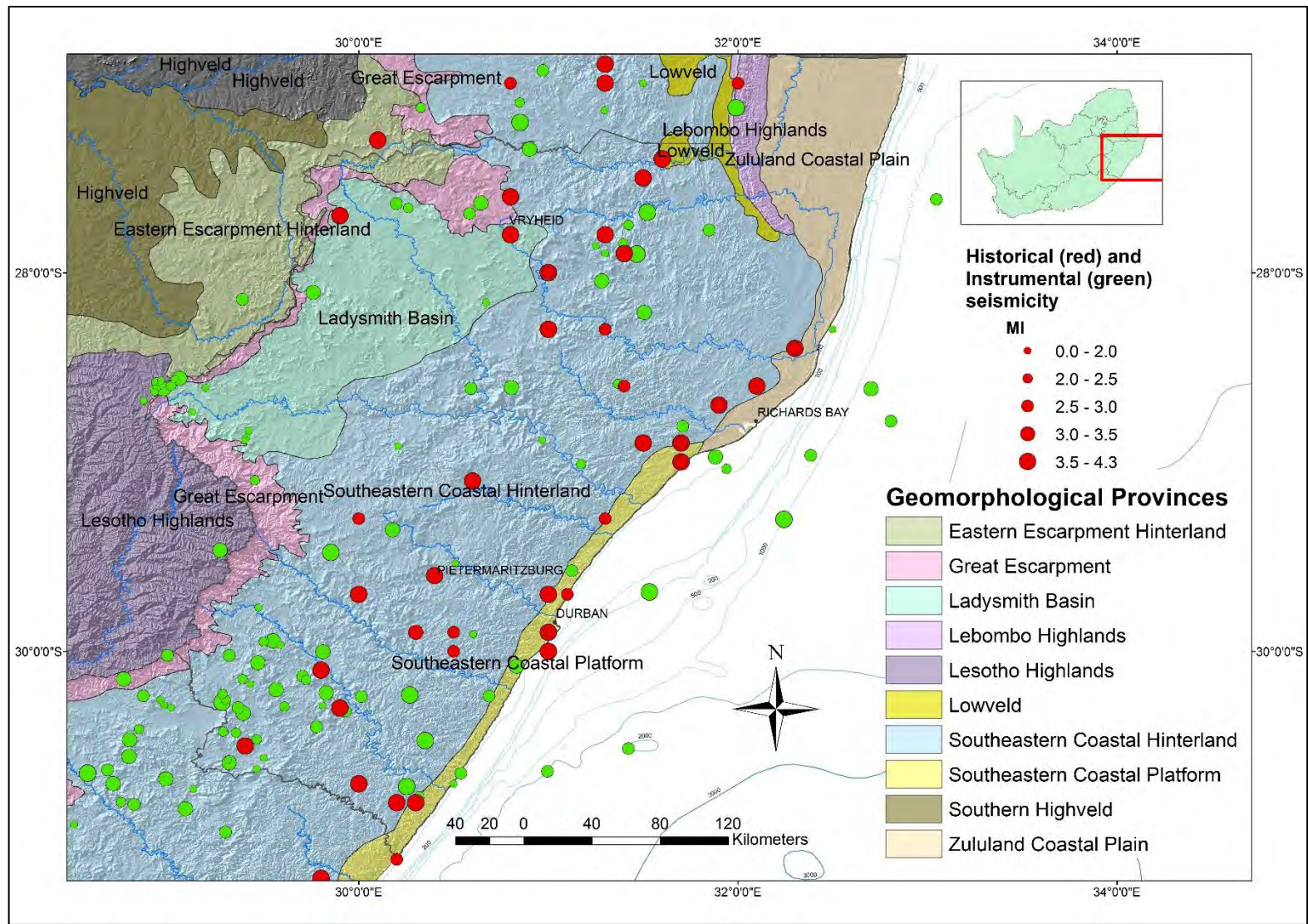


Figure 3.8 Geomorphological domains of Partridge et al. (2010)

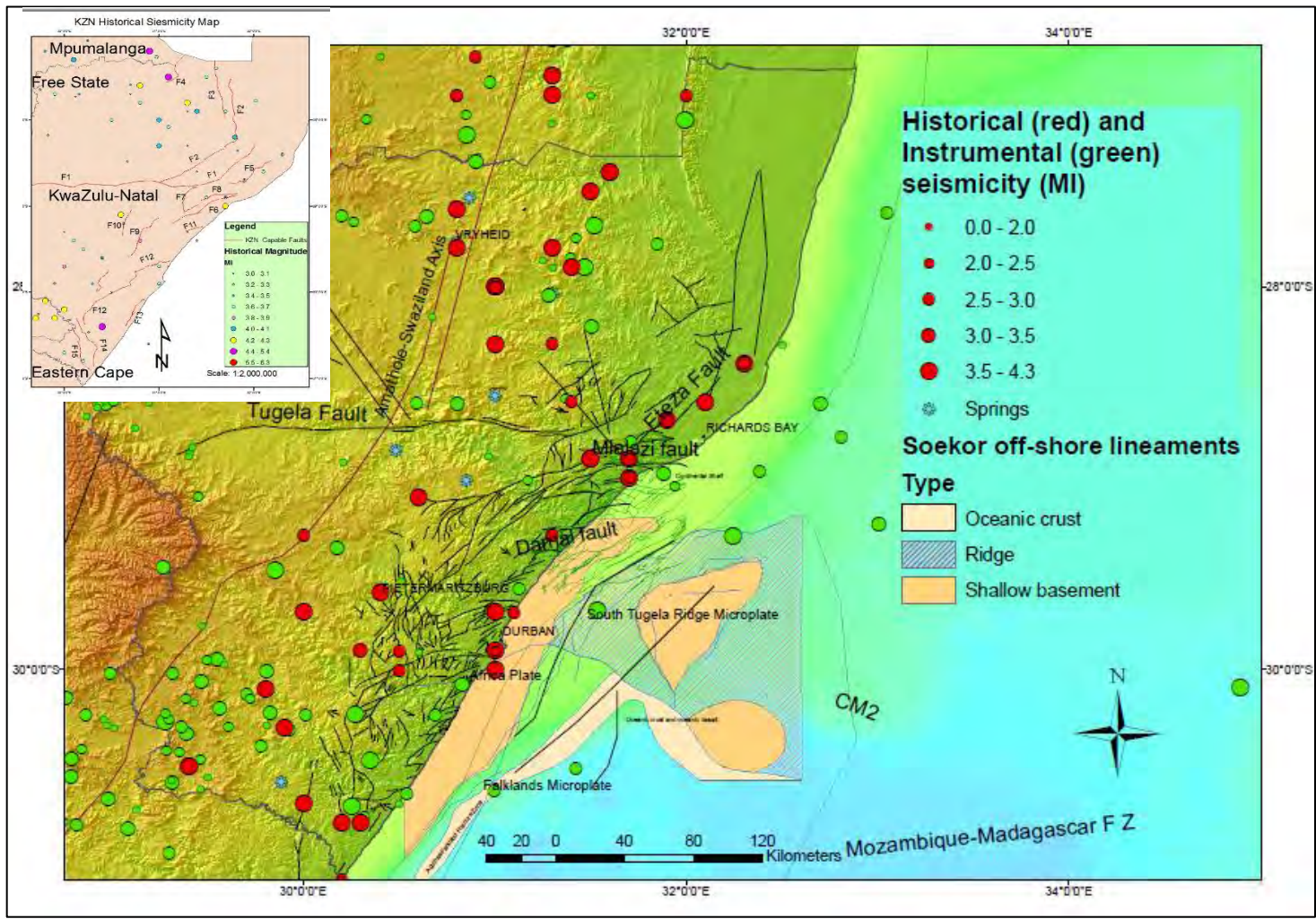


Figure 3.9 Map of structural lines contained in the 1-250K Geology (data from Council for Geoscience) and neo-tectonic structures digitized from reports referenced herein. Insert: Potentially active faults in the region from Ngoasheng (2015) study

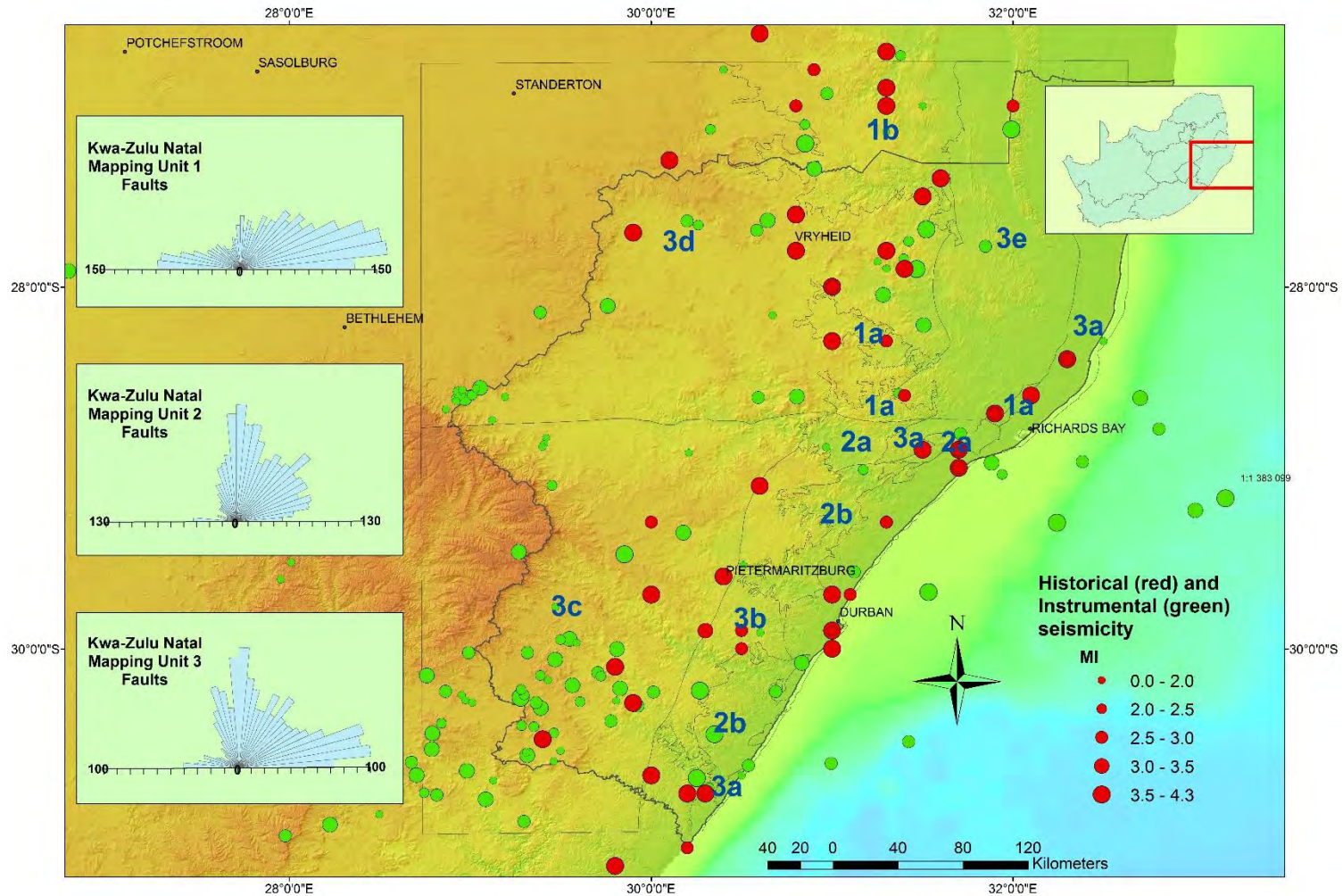


Figure 3.10 Structural domains produced by Von Veh (1994). The domains delineated correspond with major domains 1-3 which can be further subdivided into 1a, 1b, 2a, 2b and 3 a, b, c, d and e.

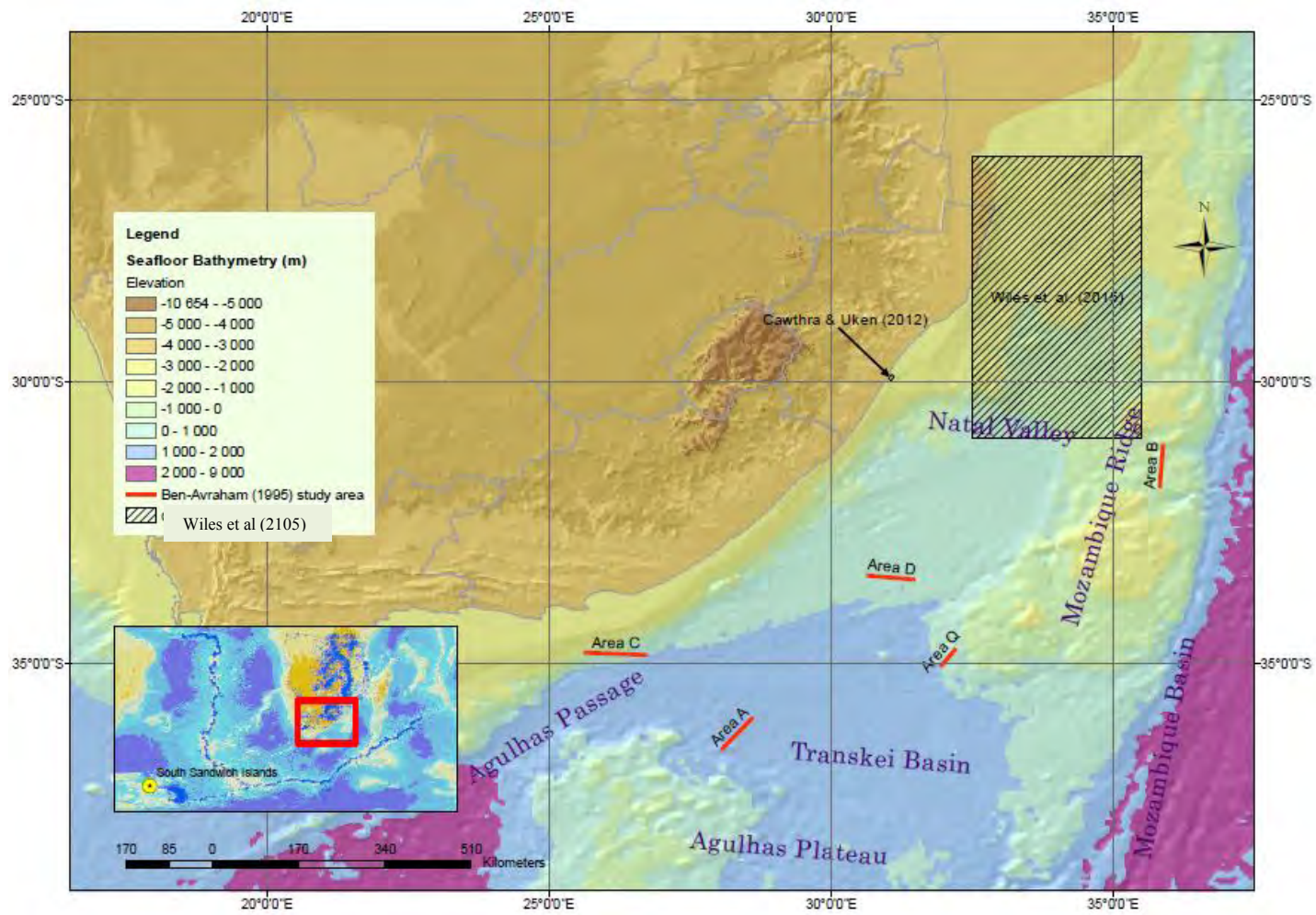


Figure 3.11 Localities of offshore study areas mentioned in the text

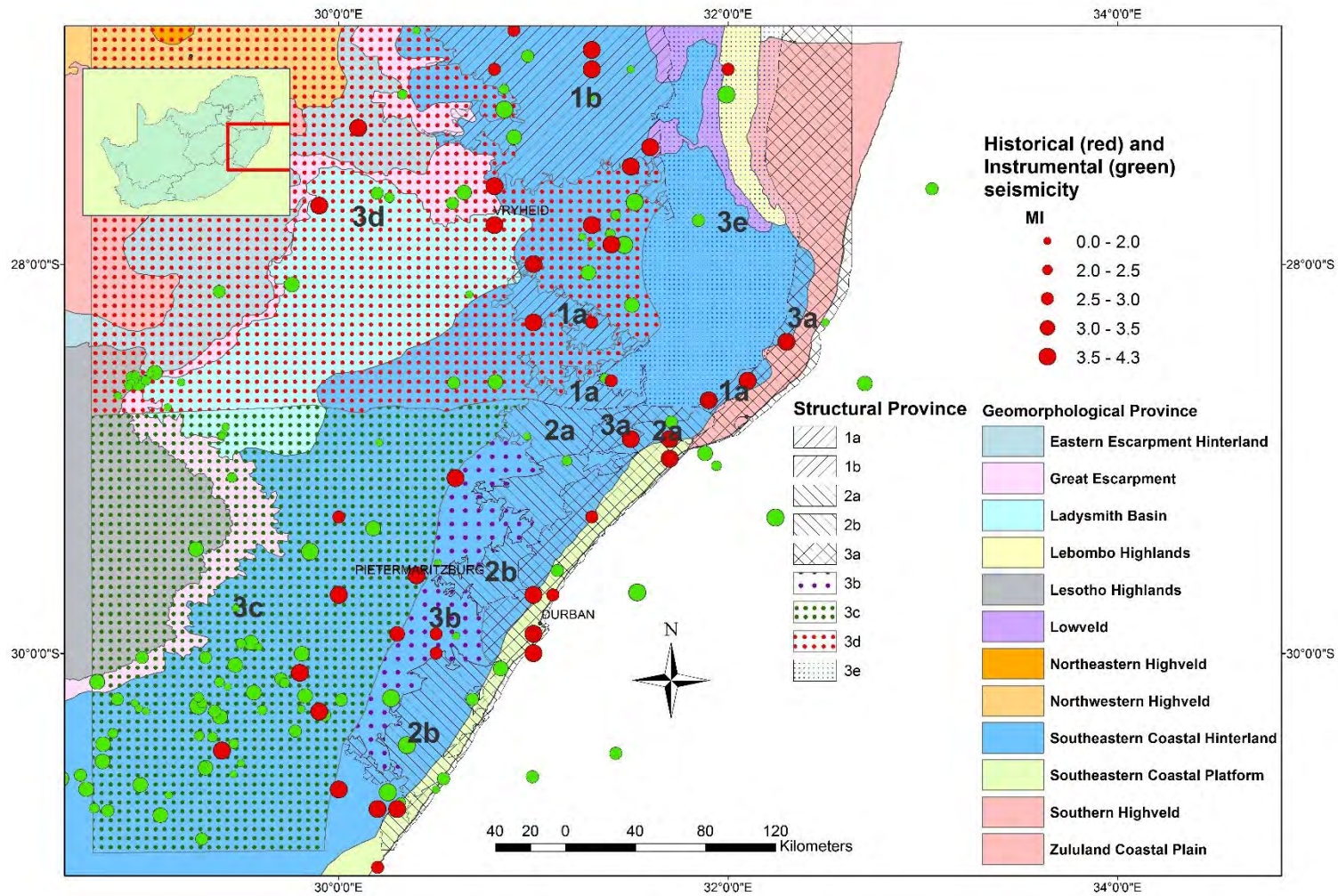


Figure 3.12 Combination of Structural Domains, geomorphological boundaries and tectonic provinces.

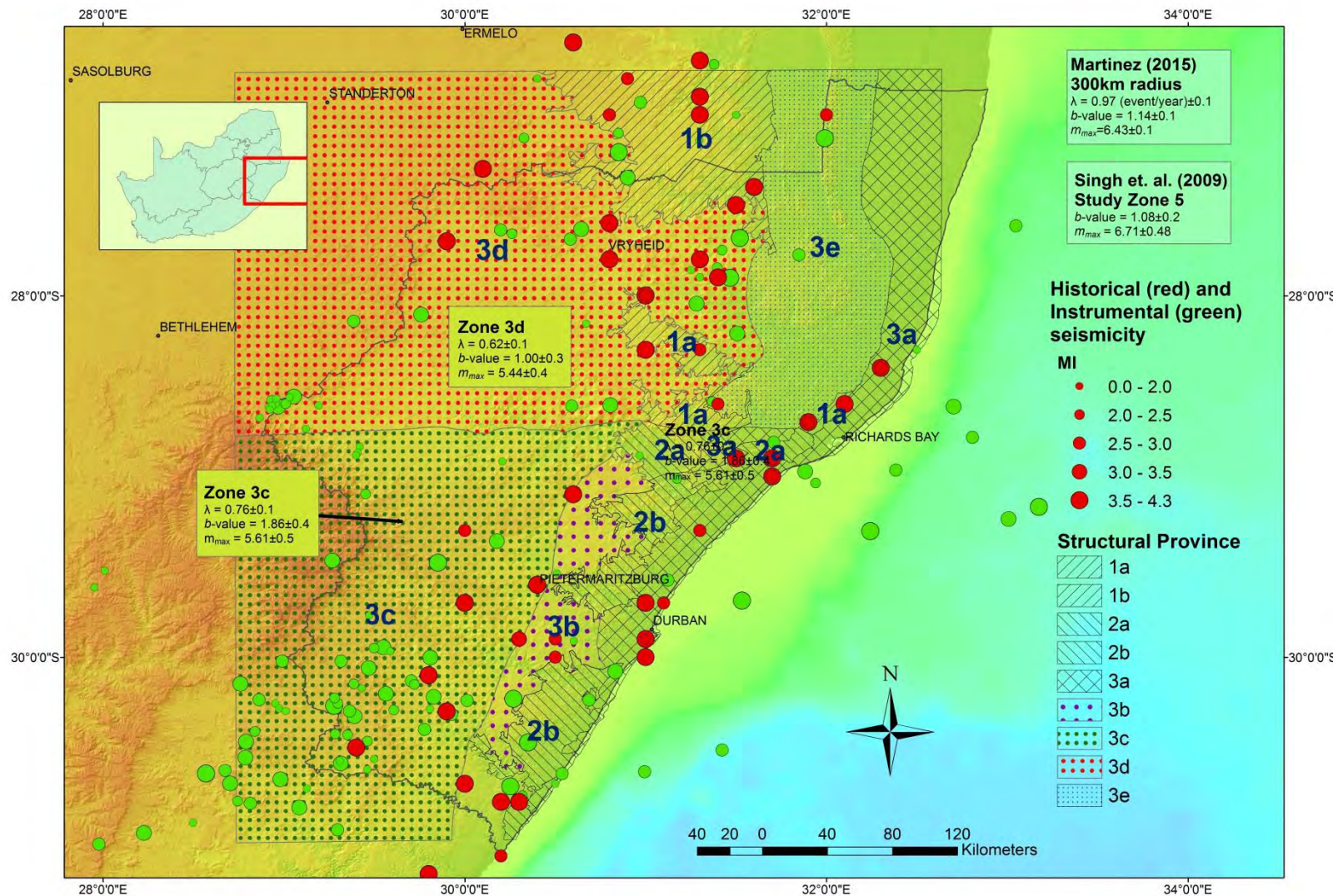


Figure 3.13 Seismotectonic interpretations considering the multidisciplinary data and research (historical earthquakes – red, instrumental earthquakes-green)

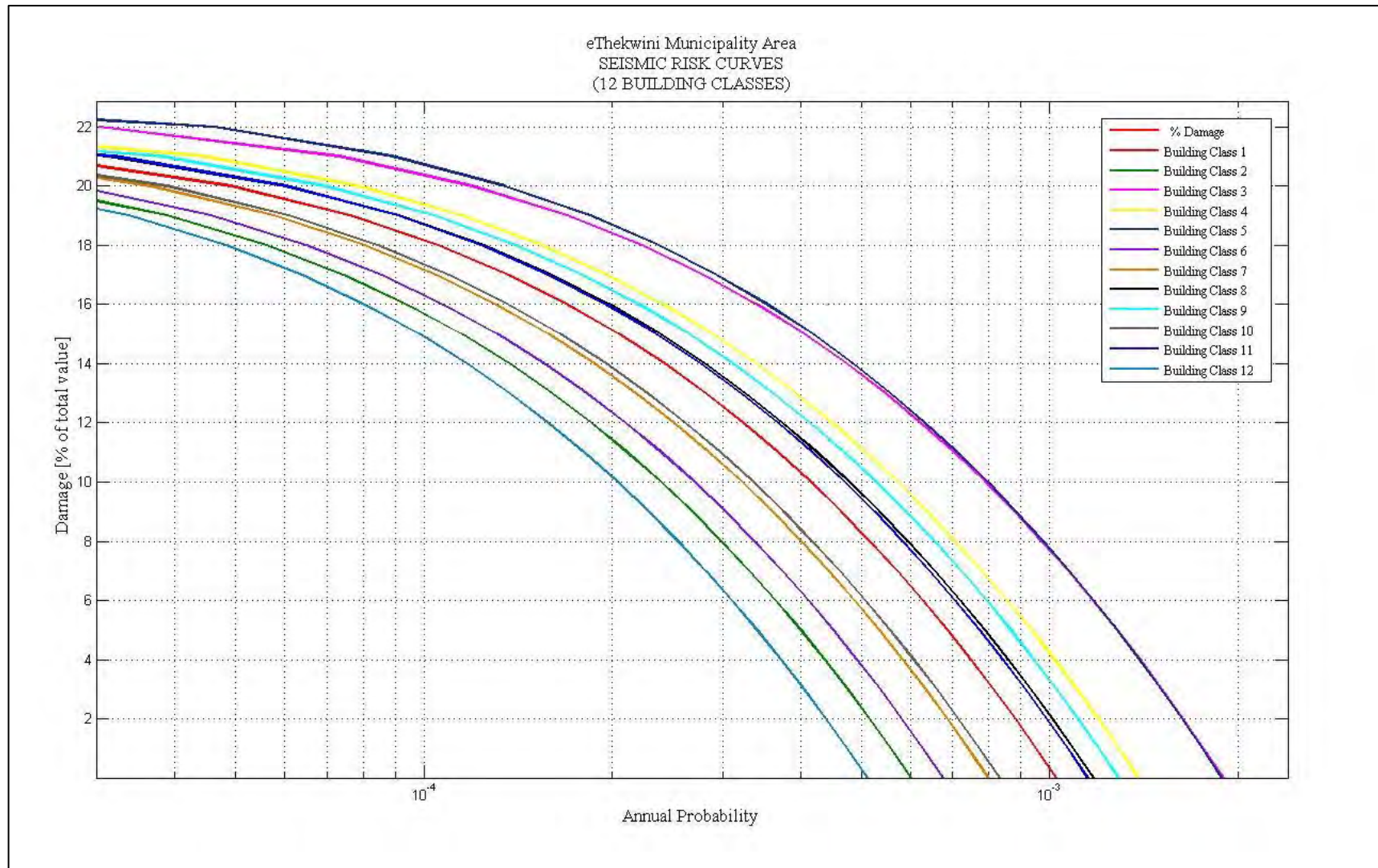


Figure 3.14 Seismic Risk Curves for the eThekweni Municipality Area by Martinez (2015)

Table 3.2 Earthquake recurrence parameters for Zone 3c and 3d.

Seismic Parameters	Zone 3c	Zone 3d	Singh et al (2009) study Zone 5	Martinez (2015) 300km radius
<i>b</i> -value	1.86±0.4	1.00± 0.3	1.08 ± 0.2	1.14 ±0.1
<i>m_{max}</i>	5.61± 0.5	5.44±0.4	6.71±0.48	6.43 ±0.1
<i>Max obs</i>	5.6	4.4		

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3.7 Acknowledgements

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CHAPTER 4:DISCUSSION AND CONCLUSION

This study was aimed towards collecting and analysing relevant datasets for seismotectonic modelling. It was further intended to improve the knowledge-base and the resolution of the model prepared by Singh et al (2009). This section highlights the achievements made towards this effort, challenges encountered and summarises the way forward for further research.

This research has shown that what was once considered as an intra-plate region with low levels of seismicity, where faults were considered inactive, has actually a moderate level of seismicity. It has been illustrated that more information is available in the earth science dataset than previously known hence a more detailed seismotectonic zonation is possible. This study provided insight into possible earthquake sources that could affect the KZN region from freshly revealed historical earthquake data. The most significant source that should be accounted for in seismotectonic investigations is that of the Mozambique Channel. The KZN region provided a unique opportunity to study an 'intraplate' region with 'moderate' seismicity levels. It was interesting to observe seismic sources originating from the coastal areas as far as SSI and the Mozambique channel. Other interesting seismic sources were the pre-existing normal Gondwana age faults and the very large Tugela fault that dissects the province. Another significant finding was the presence of a number of thermal springs situated near the Tugela fault amongst other locations. The presence of these springs does confirm to some extent neotectonic activity in the province.

It has been illustrated that the seismotectonic model consists of an amalgamation of a multidisciplinary dataset. This amalgamation can be open to interpretation in several stages which brings a significant amount of subjectivity in the model. More effort is hence required in documenting and streamlining methods for its development. At the same time effort is required in documenting the methods and in collecting the multidisciplinary dataset as well.

This work, with the assimilation of the base data and testing of modelling techniques and interpretations, provides an important baseline for future seismotectonic work in the province. For detailed investigations the fault, seismic or stress information can be investigated further at a given locality using geophysical techniques and higher resolution datasets can be acquired. Seismic monitoring can also be concentrated now along the coastline and along regions where neotectonic activity is taking place. This can be achieved by detailed field mapping at a minimum scale of 1:24K in order to detect fault activity.

One should also acknowledge that the locations of these epicentres used in this study also carries some uncertainty (some 50km) for varying reasons (insufficient station coverage and few historical

documents to provide good locations). The assessment of this uncertainty is beyond the scope of this study. There is also room to improve the historical earthquake dataset. However the instrumental seismic dataset can only be improved by densifying the seismic network. Currently the earthquake network coverage for the east coast is rather poor and hence any offshore earthquakes are not being recorded with sufficient completeness. This is a real problem because it seems that some tremors that are being felt in the region (along the coastline) are originating from offshore sources. While a large portion of the compilation of undetected tremors in Chapter 2 consisted of IDPs rather than locations of earthquake epicentres, a foundation is made for future research in this field that might search historical documents for the epicentres of these IDPs. The epicentres of these events should be located by surveying the public, newspapers and other historical documents.

Seismic events can be correlated with the old pre-existing faults. There is certainly a level of reactivation in place and an accumulation of stresses along these structures. Hence there is potential for further site investigations especially on faults identified as potentially active. Many of these faults can be located within the delineated zones. Another key dataset that is lacking is that of Quaternary faults and neo-tectonics. This data might be acquired through LiDAR.

Historical datasets on tsunami occurrences are sparse (Kijko et al., 2014 and Cawthra and van Zyl 2015) though they would be pertinent for this kind of study.

Emphasis should also be made on efforts of the CODATA initiatives to encourage data citation practices and open access to data. Initiatives are also underway for training into standards and best practice for data collection which is very important in multidisciplinary studies such as these.

The research objectives are revisited and discussed:

1. Analysis of the historical earthquake catalogue – see Chapter 2

Historical earthquake information was revisited in Chapter 2 in order to determine locations of seismic sources that can be contributing to the seismic activity in the province. We were unable to obtain earthquake epicentres due to the lack of available historical data. However we were successful in obtaining some IDPs of significant intensity to warrant further investigation. These IDP's cannot be linked to earthquakes in the national database. This then means that some significant historical earthquakes have gone undetected the national database. Many of these earthquakes are thought to originate offshore. The seismic sources that are affecting the region largely originate from the Mtubatuba area and offshore Mozambique.

There are certainly opportunities now knowing the date and time of these IDP's to scroll through the rich historical records of the early settlers particularly the English and Indian

settlers and labourers to supplement knowledge on these undetected earthquakes for records of historical earthquakes and possible tsunamis.

In 2015 and 2016 two significant earthquakes were felt all over the KZN region. On 16 June 2015 (USGS Moment magnitude 4.3) occurred in the Sundumbili region. This earthquake was felt widely in the Zinkwazi region up until Richards Bay. Locally near the Tugela river mouth, significant damage was caused to the local beach and fishing spot to the extent that some 100m of beach area was and still is entirely inundated by water. On 6 February 2016 another earthquake (CGS local magnitude 3.8) rocked the Umhlanga and Durban north coastal areas. Preliminary surveys in collaboration with CGS showed that some people felt two bouts of earthquake shaking. There is also controversy on the location of the epicentre of the earthquake – the CGS reporting that it occurred 30km offshore from Umhlanga and the USGS reported that the epicentre is located in Mpumulanga (near Hammarsdale – some 60km NW from the CGS reported epicentre). There have been no records of damage to structures. Both locations cannot be disputed because many residents in both areas reported feeling the earthquake quite strongly.

The fact that there were two bouts of shaking ties in with the reports of the earthquake that rocked the Umhlanga area on 17 August 1981 discussed in Chapter 2. Here there were in fact *three* bouts of shaking. There is certainly some slumping or fault activity in the offshore region. This is further supported by the soft sediment deformation reported by Wiles et al. (2014).

Another point that needs mentioning in relation to these two earthquakes is the vulnerability of the low-cost housing in the region. Residents in the Sundumbili area (that comprise low cost or Reconstruction and Development Program (RDP) houses) reported violent shaking of beds and furniture for both these events.

Residents in RDP homes south of Amanzimtoti (some 50km away from the reported CGS epicentre) also reported violent shaking of beds and furniture during the 2016 earthquake. Furthermore residents in low cost housing in the Mpumulanga area again felt the earthquake quite strongly compared with people working in the nearby mall some 1 km away. Hence the vulnerability of these homes should be addressed and mitigation measures should be in place to strengthen these structures to ensure residents safety. Furthermore densified seismic monitoring in the area would certainly help to understand the seismic sources at play.

2. Development of a Geo-Database for use – see Chapter 3

The geodatabase consists of a wealth of data for modelling. It was only appropriate to be used for *regional* modelling. Breakthroughs were achieved in the seismic dataset by Saunders and Botshielo (2013) who provided the much needed error ellipses of the seismic data and corresponding focal mechanisms. This then allows one to correlate faults with seismicity. Now one can easily confirm that many segments along the Tugela fault can be considered active. The fault segments correlate well with the instrumental seismicity, historical seismicity and geothermal springs in the area. It is also a region where two very different geological bodies lie adjacent to each other the KC in the north and the NNMB in the south. The Karoo sediments are deposited on these different bodies which have different densities and competencies hence we have the Karoo sediments compressing the less resistant NNMB rocks in the south of the Tugela fault as compared with the more resistant KC in the north of the fault (Figure 3.7 and Figure 3.9) (S Master 2015 pers. Comm.)

There are many faults along the coastline that correlate with the instrumental and historical seismicity. Many faults are clustered. They comprise of faults of different lengths and strike directions. These faults should be organised in different faulting systems. Thereafter one can look in detail how to correlate both the historical events (with larger location accuracy) and the instrumental events (with better location accuracy). A starting point for this would be the aeromagnetic dataset (Figure 3.6) that appears to mimic the fault patterns across the region. Looking at the aeromagnetic dataset it actually correlates better with the seismic patterns observed compared with the structural lines shown in Figure 3.9. Note that structural lines along the coastline do not continue beneath the Karoo sediments. Hence it is proposed that the active fault systems to be developed for the region should be guided by the aeromagnetic dataset. Following this ground-truthing followed by seismic surveys and monitoring should be conducted for the respective systems in order to understand fault capability.

There are still opportunities to look at the full dataset, its fit for use, the reliability and the most effective way to incorporate them in a model in an automatic way while still preserving some control on the interpretations. The database could easily be used in the SOM algorithm procedures.

3. Development of a Seismotectonic Model – see Chapter 3

The methodology for modelling was revised from Singh et al (2009) to add an extra level of subsystems – this allows for better organising of the datasets and interpretations. The Von Veh

(1994) structural model was best suited for delineation of the areal sources owing to the fact that it captured most of the understanding of the tectonics in the region. The broad (regional) domains of the NNMB and the KS suggested by Nguuri et al (2001) and observed by several other datasets (s-wave velocity, tomography, geology, aeromag, gravity). Subdomain 3 is divided into 3c and 3d by the Tugela fault that is actually a network of related faults. The Tugela fault is also the location of several springs indicating a likely region for neo-tectonic activity. The other rationale for the domain and subdomain delineation was the noticeable faulted coastal region and the relatively unfaulted western region. Also there is a noticeable variation in the lithology in the northeastern region (Mtubatuba-Richards Bay- St Lucia).

Further investigation into fault sources can be made as suggested in point 2 above but we were limited with budget and time constraints. The offshore region was not included in the model however it still remains a significant seismic source worth investigating.

More research is required on integration methods and techniques on these different datasets to effectively incorporate the different systems using the SOM algorithm

4. Development of an Earthquake Recurrence Model – see Chapter 3

Earthquake recurrence parameters could only be calculated for two zones [zones 3c and 3d] because of the lack of seismic data in the other zones. These values are comparable with other studies. Further work should focus on vulnerability assessment of urban infrastructure and risk analysis incorporating seismotectonic zones. A detailed risk assessment is required following on Martinez (2015) study in order to reassess the risk based now on the newly acquired zones and to better understand the building vulnerability of the province as performed for the Durban CBD (see Tshabalala, 2015) .

The objectives as noted above have been met as intended. With a regional KZN model one can now pin-point areas that can be further investigated to characterise the seismotectonic model more accurately.

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CHAPTER 5:APPENDICES – PEER-REVIEWED AND NON PEER-REVEIWED CONTENTS

5.1 EGU 2012 Abstract: Seismotectonic Analysis for the KZN region of South Africa

Citation: *Singh M. (2012) Seismotectonic Analysis for the KZN region of South Africa, Vol 14, EGU 2012-10491*

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Seismotectonic Analysis for the KZN region of South Africa

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Recently, devastating earthquakes and tsunamis have shocked the modern world (Japan [April 7 2011, Mw 9.0, loss of life and destruction of infrastructure, 15,457 deaths 5,389 injured, US300\$billion loss (Japanese National Police Agency 2011)], New Zealand [21 February 2011, Mw 6.3, 148 killed], Haiti [12 January 2010, Mw 7.0, estimated 316 000 killed and 300 000 injured]. These earthquakes have caused large scale damage to the built environment not to mention the high number of fatalities. The KZN coastal region is also fast developing especially towards the north of Durban CBD (Cornubia [New development near Umhlanga, 25 Billion Rands investment], Gateway/Umhlanga Business District, Moses Mabida Stadium (cost of R3.4 billion), King Shaka International Airport at a cost of R6.8 billion, Dube Tradeport to be developed next to the airport at a cost of R5 billion, as well as the development of the Richards Bay Industrial Development Zone . The KZN is home to 10 million inhabitants with a relatively denser population distribution around the Durban and Pietermaritzburg CBDs. With the increasing amount of investment towards the north coast of Durban, the population distribution will migrate to these areas. These areas now become 'vulnerable' to rare, infrequent and potentially devastating natural disasters like earthquakes. One of the first steps to understand and plan for an earthquake occurrence is through a seismic hazard and risk assessment. The seismic hazard and risk method has well been established since 1968 (see Cornell (1968); Veneziano et al., (1984); Bender and Perkins (1993); McGuire (1993); McGuire and Toro (2008); Kijko and Graham (1998); Kijko and Sellevoll, (1989, 1992)). The components of a seismic risk assessment (SRA) include several building blocks namely: the development of the earthquake catalogue, seismotectonic model, attenuation models, seismic hazard assessment (SHA), vulnerability assessment and seismic risk computations. The seismotectonic model element will be explored in further detail for this research. Preliminary investigations into a seismotectonic investigation for the province have been undertaken by Singh et al. (2011). Under the framework of this research the following tasks are planned for the KZN coastal region: i) Development of a historical earthquake catalogue ii) Development of a GeoDatabase for Seismotectonic Zonation iii) Development of a Seismotectonic Model and iv) Development of an Earthquake Recurrence Model. The author will present progress made to date towards this research.

5.2 SAGA-AEM 2013 Extended Abstract: Combining Structural Domains, Geomorphological Provinces and GPS Data for Seismotectonic Modelling of the KZN Province

Citation: *Singh, M., Akombelwa, M. and Maud, R. (2013), Combining Structural Domains, Geomorphological Provinces and GPS Data for Seismotectonic Modelling of the KZN Province, SAGA-AEM Conference, July 2013, Kruger National Park, SA*

Preliminary studies combining earth science data [geology, geophysics and seismicity] reveal that the KZN coastal regions have been subjected to significant ground motions historically. Subsequently, all new developments especially hazardous and high rise structures should incorporate a seismic design component prior to construction. Coast perpendicular and coast parallel faults correlate with seismic events recorded for the region. For seismotectonic modelling, the following additional datasets are compiled: structural domains for the province which provide a tectonic basis for seismotectonic modelling; regional geomorphological provinces which provide a geodynamic basis for seismotectonic modelling and GPS measurements to characterize regional and local plate motions.

Seismotectonic modelling used for seismic hazard and risk assessments requires a complete comprehension of the geology, tectonics, palaeo-seismology, regional geophysical anomalies, historical and instrumental seismicity, and other neo-tectonic phenomena like, relative plate motions and current tectonic plate stresses. A study of the seismic catalogue (Singh et al 2013) reveals that the region in question has a significant level of seismic activity. From the seismic catalogue, NE-SW coast parallel patterns of seismic occurrence can be seen. This pattern correlates with the geology outcropping in a similar coast parallel orientation. The mapped faults have two distinct orientation NE-SW coast parallel patterns in the south west, and NW-SE coast perpendicular orientations in the north. Several correlations can be made with the mapped faults and the seismic locations. From the regional geophysics datasets the extent/boundaries of the basement geological provinces of the Achaean Kaapvaal craton and the mobile Namaqua-Natal Mobile Belt province can be located. Higher resolution earth data is now available and digitised - like structural domains for the province which provide a tectonic basis for seismotectonic modelling (Von Veh 1994); regional geomorphological provinces which provide a geodynamic basis for seismotectonic modelling (Partridge et al 2010) and GPS measurements to characterize regional and local plate (Malservisi et al 2011).

Structural domains

Structural domains provide insight to the underlying tectonic forces at play when trying to understand earthquake causes. Von Veh (1994) defined three broad structural domains by analysing fault, dyke and lineament data. These domains were further subdivided based on geological characteristics. In total 9 subdomains were delineated. The strike frequency distribution of faults, dykes and lineaments were analysed for each domain. The

direction of maximum principal stress that prevailed during the different tectonic events was also provided for each sub domain. No obvious patterns can be observed when overlaying the seismic events with the structural domains. The value of these domains will come into play at specific sites where earthquakes and fault mechanisms are being investigated.

Geomorphological domains

Partridge (2010) identified 34 provinces and 12 sub-geomorphic provinces. These provinces are generally geographic regions on the earth's surface that are subject to the same erosional parameters and are similar in terms of structure, shape and mineral composition. Essentially they were identified from macro-reaches that were subsequently classified in terms of slope and cross sectional width, sediment storage potential etc. Principal component analysis was used for the data analysis. For the KZN region a regional sub-domain was identified with the Great Escarpment showing prominence. Numerous rivers drain from the escarpment to the coastline. The St Lucia area has a remarkably different province from the broad province identified for KZN region. This is an interesting observation as the largest historical earthquake in the province originated in this region.

GPS

Malservisi et al (2011) analysed GPS data from the South African Trignet network. They found that the cratonic regions in SA is stable with a relatively larger deformation rate in the Cape Town region. They also found deformation possible along the southern coast and along the Mozambique belt. On a more broader view the African continent behaves like a rigid plate with motions within 2mm/year with a clockwise rotation of the South African region with respect to the Nubian region. In the most part of their conclusions, data was lacking to confirm hypothesis. In this case this type of data along with its quality and uncertainty should be incorporated and measured in some way for the seismotectonic modelling.

These additional datasets should be combined effectively to understand the seismotectonics in the region. One should have an understanding of the methods used in combining the datasets and provinces, as well as a handle on incorporating quality of the data and uncertainty of the data and results. The seismotectonic modelling will be undertaken in follow-up work.

5.3 Position IT 2014 Article: Geo-Database compilation for Seismotectonic investigations for the KZN coastal regions

Citation:

Singh, M., Akombelwa, M. and Maud, R. (2013), Geo-Database compilation for Seismotectonic investigations for the KZN coastal regions, SASGI Conference, Emperor's Palace, Jbg, 23-24 July 2013

Singh, M., Akombelwa, M. and Maud, R. (2014), Geo-Database compilation for Seismotectonic investigations for the KZN coastal regions, Position IT, July 2014, EE Publishers (PTY) Ltd.

Abstract

Seismotectonic modelling used for seismic hazard and risk assessments requires a complete comprehension of the geology, tectonics, palaeo-seismology, regional geophysical anomalies, historical and instrumental seismicity, and other neo-tectonic phenomena like, relative plate motions and current tectonic plate stresses. This paper shows progress made in compiling available geospatial data relevant for this kind of modelling at the best resolution available and elaborates their importance in understanding the seismic load for the region. A study of the seismic catalogue reveals that the region in question has a significant level of seismic activity, and ground motion parameters should be incorporated in the design of critical structures. At this stage visual correlations with the seismic catalogues and available geo-data were made in order to ascertain where further analysis is required. From the seismic catalogue, NE-SW coast parallel patterns of seismic occurrence can be seen. This pattern correlates with the geology outcropping in a similar coast parallel orientation. The mapped faults have two distinct orientation NE-SW coast parallel patterns in the south west, and NW-SE coast perpendicular orientations in the north. Several correlations can be made with the mapped faults and the seismic locations. From the regional geophysics datasets the extent/boundaries of the basement geological provinces of the Achaean Kaapvaal craton and the mobile Namaqua-Natal Mobile Belt province can be located. Other important studies on the geomorphological provinces, regional plate motion, natural springs, seismic tomography and structural provinces are still being compiled.

Keywords

Seismotectonics, earthquakes, seismic hazard, seismic risk

Introduction

Development in the KwaZulu-Natal coastal regions is fast paced. The area is attracting multi-billion rand investments from both national and international investors for major infrastructure development projects. To name a few: *In Durban central-* Transnet's proposed port infrastructure upgrade and EThekwinini's upgrading of

the Point harbor area, *La Mercy* upgrading of infrastructure at the Dube Trade port in the vicinity King Shaka International Airport and the infrastructure of the airport itself and *Cornubia* - an extensive new housing and infrastructure development project that will extend from the already developed Gateway precinct to as far as the new airport. These civil projects make the region probably one of the fastest growing area currently in South Africa (SA).

With infrastructure development, supporting power and water facilities and population density increase come an increase in vulnerability to rare natural disasters like earthquakes – which if understood properly could have their disastrous effects minimized. Recent earthquakes in Japan, New Zealand and Haiti have shown the need for proper infrastructure design and the world has vividly seen the wrath and havoc earthquakes can have on a country and its economy.

New infrastructure should incorporate seismic loads in their design hence seismic hazard and risk assessments should be performed on a local scale. These assessments are critical for the construction of state of the art critical facilities like hazardous and high rise structures. A seismotectonic model is a critical building block for these evaluations which comprises as a start a multidisciplinary geo-database for understanding the root cause of earthquakes and classifying those regions that have similar properties for earthquake occurrence.

The KZN coastal areas have experienced several potentially damaging earthquakes historically albeit these earthquakes occurred at a time when it was less populated and built-up – hence there is very little memory or record of earthquake damage. Figure1 shows the distribution of isoseismal maps [curves delineating areas with different seismic intensities from each other in Modified Mercalli (MM) scale of [1] where potentially damaging intensities to infrastructure start from MM Intensity IV upwards. Historical reports of damage to the KZN coastal areas have been reported since 1932. These earthquakes are reported to originate from different sources even neighboring countries like Mozambique. Note that the damage reported was significantly less as compared to if there were to be a repeat of the same earthquake today, mainly due to the rapid change in infrastructure and development.

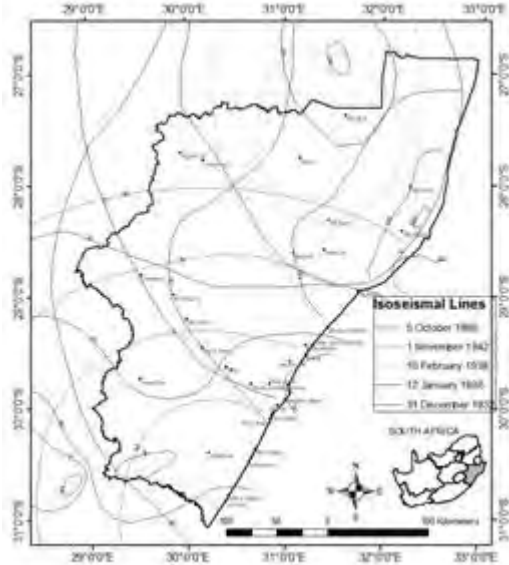


Fig. 1: Isoseismal maps of significant earthquakes that have occurred within the province (from [2])

While seismic hazard maps were calculated for South Africa [3, 4, 5] the methodology used for the calculations of these maps were based on ‘seismotectonic zone-free’ methods (mainly because the seismotectonic model for the region was poorly understood). Regulations for seismic design of critical structures like Nuclear Power Plants, Bridges, Tunnels, LNG Terminals, requires that seismotectonic models in some form be incorporated in the seismic hazard assessments (SHA) (see IAEA Seismic Safety Series; U.S. Nuclear Regulatory Commission Seismic Regulatory Guides; European building code Eurocode; National Nuclear Regulator’s guidelines for seismic design).

While there are several agreed methodologies for deriving the seismotectonic model [6-12] and there are several methods for SHA [13-20], in all approaches, similar kinds of ‘geo-data’ are required – for which its completeness, availability and resolution around the world differ. This work aims to put together the available data from literature and relevant organizations responsible for the data collection. Its status in terms of completeness, resolution and value to the seismotectonic modelling will be assessed in follow up work. This work forms the first step for the seismotectonic modelling process.

The first publication for SA that built up a comprehensive multidisciplinary geodatabase of this nature was that of [21] and thereafter [22]. Several gaps were identified in the database if it were to be used for SHA for critical structures. [23] proceeded to build a regional model despite the incompleteness in the datasets. Further [24] assimilated several other important datasets in order to investigate the potential for groundwater on a regional scale in SA. Other important work is that of [25] that assimilated geo-data for use in development of a landslide susceptibility map for the province.

[26] Summarises the essential parameters required for a seismic source model that can be used in SHA. Two types of earthquake sources are required fault sources and areal sources. *Fault sources* are typically modelled as a three dimensional fault surfaces and details of their behaviour are incorporated into the source characterisation and *Areal sources* are regions where earthquakes are assumed to occur randomly with no clear association with any of the faults that might be included in the seismic source model. For fault sources to be included in the analysis basic geometric source parameters that are required include the fault location, dip and thickness of the seismogenic zone. For the recurrence parameters one needs to include the recurrence model, recurrence rate – which can be obtained from the slip rate or average recurrence interval for the maximum event, slope of the recurrence curve (b-value), and maximum magnitude.

While the inputs to obtain fault and areal sources are so complex, the risk implication varies considerably – considering the investment required for increasing seismic safety for design. Therefore it is imperative in the modelling to move from a more qualitative to a more quantitative methodology. There is a need for one to be able to propagate errors, where expert judgement is supported by data and is verifiable. All datasets should have room for updating at a later stage. The seismotectonic modelling analyst should be accountable and his hypothesis should be traceable or data-supported.

Therefore the style of this review is designed to start with raw data and to track the interpretative outputs in order to understand completeness and uncertainties. Ideally one should also be able to document multiple interpretations. For modelling that requires data from a multidisciplinary field this is often impossible unless the data has been acquired strictly for this modelling purpose and all processes are documented.

In this study, the following datasets are presented the seismic history of the region, the regional geology and the regional geophysics. Several other datasets are still in the process of being digitized.

Seismic History

The Council for Geoscience provided both a historical (pre-1970) and instrumental catalogue of seismic events for the KZN province (see Fig. 2). Additional historical events have been found in literature but are presently being validated. A project is also underway to validate all seismic events in the CGS catalogue in terms of location and magnitude accuracy. Presently the seismic stations are sparsely distributed regionally making the threshold of earthquake sensitivity equivalent to all magnitudes greater than and equal to 3.

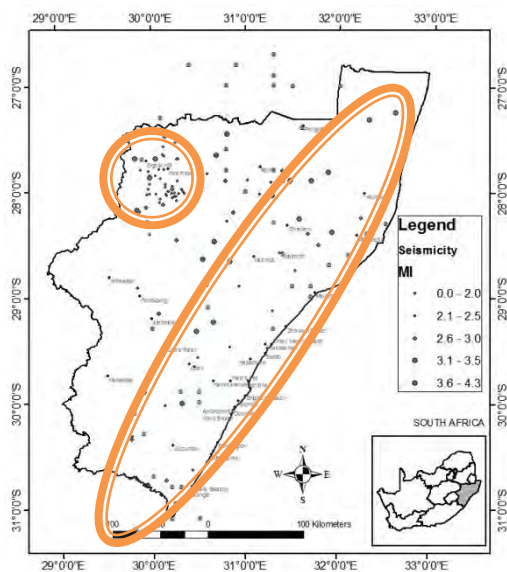


Fig. 2: Historical and Instrumental seismic events that occurred within the province

There are a total of 177 earthquakes on record with local magnitudes (M_L) within range of 2-4 from 1970-2012. In the historical catalogue there are 62 earthquakes on record with local magnitudes (M_L) within range of 1.5-6.3 from 1906-1969.

The largest earthquake occurred in 1932 of M_L 6.3 in the St Lucia area. Its effects are well documented in [27]. This earthquake was located in the sea offshore the Zululand coast. Shocks were reported in Port Shepstone, Kokstad, Koster, and Johannesburg (some 500 km away). The nearest point on land to the epicenter was Cape St. Lucia, where Modified Mercalli Intensity (MMI) of IX was assigned on the evidence of sand boils and cracks in the surface, but the damage in this area was small possibly because it was uninhabited. In the severely shaken areas, poor-quality houses (built of unburned or half-burnt bricks or other low-quality materials) were severely damaged. In well-built houses, small cracks were occasionally seen but the structures did not suffer major damage. The phenomenon of site-effects was clearly displayed in the observations of the after effects of this event. Structures built on thick sand were undamaged, while those built on alluvial sands suffered severe damage. Changing rock types in the area also had a strong influence on the attenuation of the seismic wave.

From evidence of its effects, [27] argue that this earthquake was probably caused by slip along a fault in the sea striking in a SSW-NNE direction parallel to the coast.

There is no obvious pattern when looking at the spatial distribution of the earthquakes except two very broad patterns as indicated. Towards the north - clustering of events occur in the north-west from blasting in the coal fields (containing events from the instrumental period only). An almost linear band of about 100km extent of random occurrences of both historical and instrumental earthquakes can be located trending in a NE-SW coast parallel direction.

Geology and Faults

The lithological units outcropping in the province is shown in Fig.3. [28] Provided a generalized summary of the rock units outcropping into the province. The rocks in the region are of Achaean (3800-2700Ma) to Cenozoic (65Ma –recent) in age. The older rock units outcrop towards the northern extent of the province towards the Swaziland border. On the eastern coastline, the Cenozoic Zululand Group silt and sandstone and unconsolidated sediments can be found. Most of the central part of the province consists of the Paleozoic to Mesozoic (300-180Ma) Karoo Supergroup (KS) sediments. The younger Proterozoic rocks (2500-490 Ma) of the Natal Group Sandstone (NGS) and the Natal Metamorphic Province (NMP) can be found outcropping in a NE band between Durban and Pietermaritzburg. From Pietermaritzburg up to Lesotho in a westerly direction one would find rock outcrops of the KS.

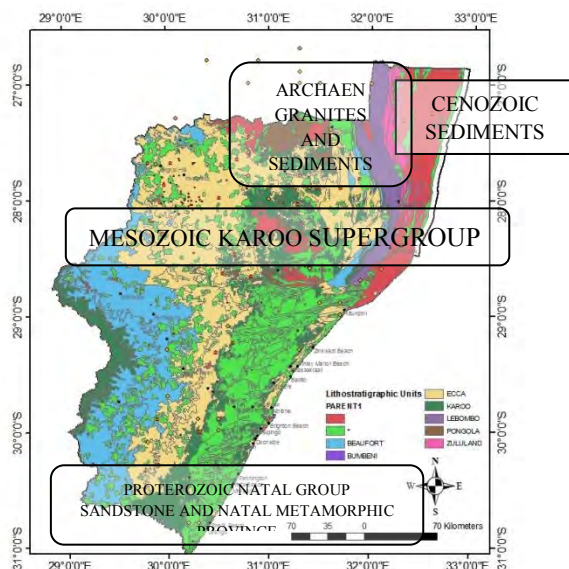


Fig. 3: Lithological units of the KZN province (from the 1:1000 000 Regional Geology Map of the Council for Geoscience). The seismic event location is superimposed on the lithological units.

On first observation the only correlation with the north easterly trend of the seismic locations identified earlier is the linear outcropping trend of the sediments of the NGS and the NMP. However this NE seismic trend extends

into the sediments of the KS. A more detailed classification scheme is required than that of [28] to identify the different rock units and their relative spatial and age relationships. Hence higher resolution geology data has been collected and is being assimilated [KZN Regional geology 1:250 000 scale, Durban 1:50 000 scale, St Lucia and Richards Bay, Verulam and Maputuland and offshore bathymetrics].

The incipient break-up of the Gondwana supercontinent 183 Ma formed fractures and planes of weaknesses that acted as conduits for lava and formation of dolerite dykes and sills. After the separation of Africa and Antarctica at about 140 Ma marine sediments of the Cretaceous Zululand Group were deposited in the newly opened Indian Ocean.

Major faults mapped in the province are superimposed on the seismic catalogue Fig.4. [29], [30] and [31] described consistent trends in the fault directions in the province essentially coast parallel NE-SW faults and coast perpendicular NW-SE faults. These distinct groups occur at the interface with the sediments of the KS and the Pongola Supergroup (NW-SE faults) and at the interface between sediments of the KS and the sediments of the NGS and the NMP. The E-W fault line is also a prominent feature and occurs within the KS.

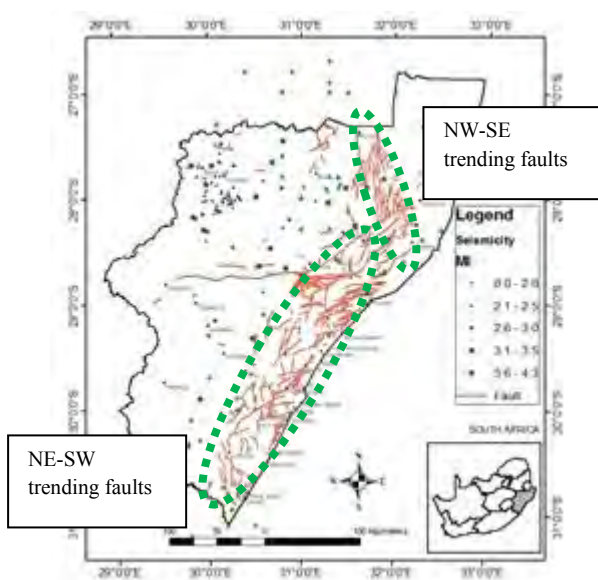


Fig. 4: Mapped faults in the KZN province (from the 1:1000 000 Regional Geology Map of the Council for Geoscience). The seismic event location is superimposed on the faults.

[29] looked specifically at the Durban area and found relative displacement of faults of a few centimeters to tens of meters. [32] Described faults in detail that had displacements of 300m in places. Normal faults are dominant in the Durban area and are consistent with extensional palaeostresses acting at the time of faulting.

Interestingly there are several correlations with the seismicity and the mapped faults in the area. Until the seismic event locations uncertainties are assessed, accurate correlations cannot be made. Work in progress includes understanding and classifying the faults such as mechanisms, stress orientations, age of faulting, displacement amounts and evidence for reactivation during the Quaternary period.

Geophysics

Geophysical investigations (*e.g.*, gravity, magnetics, and seismic anisotropy) provide a better understanding of the subsurface geology of the Earth. Regional aeromagnetic and gravimetric maps of the province are shown in Figs. 6 and 7. The seismicity data are superimposed on these maps.

Gravity data provide information about densities of rocks underground. Generally, gravity highs indicate the presence of relatively dense rocks, and magnetic anomalies are caused by rocks with abundant magnetite in them. Very high-intensity anomalies (more than 50 milli-gals or more than 200 gammas) typify major changes in rock type, usually (but not always) in basement rocks. Most sedimentary rocks (with the exception of banded ironstones) contain little magnetite, so generally we are dealing with igneous and metamorphic rocks [33].

From the geophysics data, the regional geological provinces can be determined [34]. The southern extent of the Achaean KC is indicated on the figures and the lower province is called the Namaqua-Natal Mobile Belt (NNMB). This boundary also falls in the same vicinity of the EW trending fault mapped through the province. The sediments of the KS overlay these provinces in most cases. Note that in both these figures the patterns formed by the geophysical signatures correlate to a large extent with the geological provinces beneath the Karoo sediments.

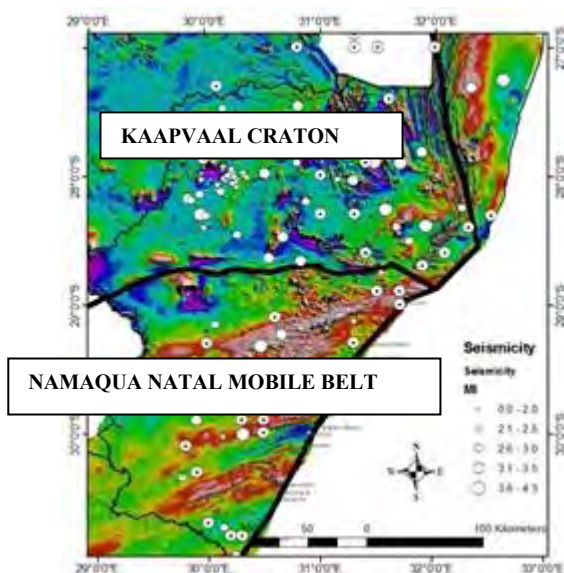


Fig. 5: Regional aero-magnetics of the KZN province together with the seismic event locations.

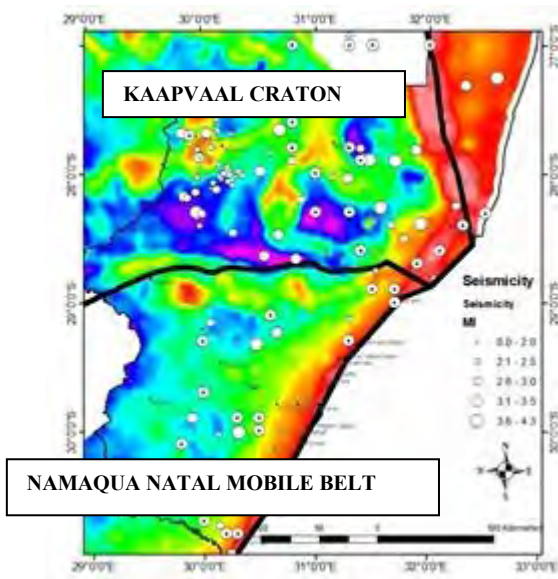


Fig. 6: Regional gravity of the KZN province together with the seismic event locations.

The rocks in the NNMB provide locally high magnetic signatures. The regional gravity map also maps the high density rock types along the coastline. No other direct correlations can be made with the seismicity and the geophysics at this stage.

Higher resolution datasets are available and is being assimilated for further analysis.

Other Databases and Work in Progress

Other work that is being assimilated is: structural domains for the province which provide a tectonic basis for seismotectonic modelling [31]; regional geomorphological provinces which provide a geodynamic basis for seismotectonic modelling [35], GPS measurements to characterize regional and local plate [36]; naturally occurring springs like Lalani, Shushu and Natal Spa that occur usually at deforming ground areas at [37, 38] and local evidence of neo-tectonic deformation/faulting.

Conclusions

The region has experienced a significant level of seismic activity historically. Visual correlations of the seismic catalogue locations show NE-SW coast parallel patterns of seismic occurrences. This pattern correlates with the geology of the NMP and the NGS outcropping in a similar coast parallel orientation. The mapped faults have two distinct orientation NE-SW coast parallel patterns in the south west and NW-SE coast perpendicular orientations in the north. Several correlations can be made with the mapped faults and the seismic locations.

From the regional geophysics datasets the boundaries of the basement geological provinces of the Achaean KC and the NNMB can be located. Other important studies on the geomorphological provinces, regional plate motion, natural springs, seismic tomography and structural provinces are still being compiled.

Preliminary evidence has shown that the region has significant levels of seismicity and strong evidence of locally tectonic active regions. Hence ground motion parameters should be incorporated to reduce economic and population vulnerability to earthquakes.

Acknowledgement

This work is funded by the University of KwaZulu-Natal and the National Research Foundation. The CGS provided the regional geology, regional geophysics and historical and instrumental seismic data. Mr. Ian Saunders of the Council for Geoscience provided technical assistance with the catalogue. Kerissa Naidoo, Maruska Ramdeyal and Naomi Kunju of UKZN provided technical assistance on the reference database.

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5.4 Africa Array 2014 Abstract: Seismotectonic Interpretations of Seismic and Structural data for the KZN Province of South Africa

Citation: *Singh, M., Akombelwa, M. and Maud, R. (2014). Seismotectonic Interpretations of Seismic and Structural data for the KZN Province of South Africa Africa Array Workshop, Wits University, January 2014*

Abstract

A seismotectonic interpretation is made from analysing both the earthquake and structural systems. A methodology is designed from methods used in France and Italy. Geo-spatial data like geology, tectonics, regional geophysical anomalies, historical and instrumental seismicity are considered. Because of incomplete records and uncertain locations, efforts were made to improve the database. Additional historical epicenters and Intensity Data Points have been found from various sources. For recorded events, their location and magnitude were re-assessed and all the explosions due to coal mining were removed. A comprehensive geo-database has been created which contains all the original reports, shape-files and maps that can be revisited when re-testing or updating of the model is required. What once was considered as a diffuse seismotectonic region with low levels of seismicity and where insufficient, uncertain and incomplete data existed – we now have datasets that are more complete and have higher levels of accuracy. Earthquake epicentres from both the historical and instrumental record as well as the occurrence of thermal springs correlate with old Jurassic faults. The seismotectonic interpretation is explained in a structured way where assumptions can be effectively tracked and recorded.

5.5 Africa Array 2015 Abstract: Analysis of possible sources of some unregistered historical earthquake tremors that affected the KwaZulu-Natal coastal regions of South Africa for seismotectonic investigations.

Citation: *Singh, M., Akombelwa, M. and Maud, R. (2014). Analysis of possible sources of some unregistered historical earthquake tremors that affected the KwaZulu-Natal coastal regions of South Africa for seismotectonic investigations. Africa Array Workshop, Wits University, January 2015*

Abstract

Historical earthquake information forms a critical dataset for seismotectonic investigations that can be used seismic hazard (SH) investigations of hazardous and high rise structures and national SH maps. This study systematically interrogates historical earthquake data for the region from various sources in order to have a better understanding of the origins of the larger earthquakes. Several previously undocumented earthquakes were found that can supplement the national catalogue. Various sources are postulated as origins of these tremors, namely local sources located in Mtubatuba and offshore sources as in the Mozambique Channel. These results re-emphasise the need to better understand the coastal environment for seismotectonic characterisation and to densify the seismic network towards the eastern coastline.

5.6 Natural Hazards 2015 Publication: Geo-Database compilation for Seismotectonic investigations for the KZN coastal regions

Citation: Singh, M., Akombelwa, M. and Maud, R. (2014). Analysis of possible sources of some unregistered historical earthquake tremors that affected the KwaZulu-Natal coastal regions of South Africa for seismotectonic investigations. *Natural Hazards* (2015). 75:2279-2289. DOI 10.1007/s11069-014-1425-8.

Nat Hazards
DOI 10.1007/s11069-014-1425-8

ORIGINAL PAPER

Analysis of possible sources of some unregistered historical earthquake tremors that affected the KwaZulu-Natal coastal regions of South Africa for seismo-tectonic investigations

Mayshree Singh · Mulemwa Akombelwa · Rodney Maud



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Abstract Historical earthquake information forms a critical dataset for seismo-tectonic investigations that can be used seismic hazard (SH) investigations of hazardous and high rise structures and national SH maps. This study systematically interrogates historical earthquake data for the region from various sources in order to have a better understanding of the origins of the larger earthquakes. Several previously undocumented earthquakes were found that can supplement the national catalogue. Various sources are postulated as origins of these tremors, namely local sources located in Mtubatuba and offshore sources as in the Mozambique Channel. These results re-emphasise the need to better understand the coastal environment for seismo-tectonic characterisation and to densify the seismic network towards the eastern coastline.

Keywords Historical earthquakes · South Africa · Seismo-tectonics

1 Introduction

An earthquake catalogue is an important resource that can be used to assess the probability of future occurrences of earthquakes in a given region in order to build seismic resistance into engineering structures. While the instrumental part of the earthquake catalogue is critical for recording earthquakes as they occur, the catalogue should also reflect historically recorded events of generally larger magnitudes that usually have occurred less frequently (Ambraseys 1971). Historical seismic records have been compiled into national earthquake catalogues worldwide. Some examples include for Europe (Rubbia 2004), India (Rao and Rao 1984), Japan (Usami 1979) and China (Lee et al. 1976).

5.7 SAGA 2015 Extended Abstract: Earthquake recurrence parameters for KwaZulu-Natal Province

Citation: Mapuranga, V. and Singh, M. (2015). Earthquake recurrence parameters for the KwaZulu-Natal Province. SAGA Conference, September 6-19, 2015, Drakensberg, South Africa.

Earthquake recurrence parameters for KwaZulu-Natal Province

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BIOGRAPHY

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SUMMARY

Application of modern science is essential in raising awareness and mitigating risks associated with natural disasters such as earthquakes, droughts. KwaZulu Natal is faced by a burgeoning urban population and plans are already in motion to spend a billions of rands to wards the expansion and rehabilitation of infrastructure such as ports, airports, shopping malls etc. The occurrence of a strong earthquake makes the province vulnerable to devastating consequences such as loss of lives and economic damage.

It is with this view that updated seismic hazard maps have to be available to relevant government authorities and engineers so that informed decisions are made in land use planning, construction as well as improved building design. Earthquake recurrence parameters are an important input in the evaluation of seismic hazard and in this study they have been calculated based on maximum likelihood procedures.

Keywords: m_{max} , b -value, activity rate.

INTRODUCTION

The accurate evaluation of earthquake recurrence parameters is a critical step in seismic hazard analysis and is also used in the engineering and insurance industries. The initial step before the evaluation of recurrence parameters is the delineation of seismic source zones. A seismic-tectonic model that is based on a multi-disciplinary geodatabase has already been developed for KwaZulu-Natal (KZN) and is shown in Figure 1 below. Data used for the formulation of this seismic-tectonic model is inclusive of geology, tectonics, palaeo-seismology, regional geophysical anomalies,

Historical and instrumental seismicity



Figure: KwaZulu-Natal seismic zones based on Singh et al. (2014)

The Gutenberg-Richter relationship

The Gutenberg-Richter relationship (Gutenberg and Richter (1944)) is the most frequently used model of earthquake magnitude recurrence. The relationship is

$$\log(n) = a - bM \quad (1)$$

where n is the number of earthquakes with a magnitude M whereas a and b are parameters. The earthquake magnitude lies within the domain (m_{min}, m_{max}) , where m_{min} is the level of completeness of the earthquake catalogue and m_{max} is the maximum possible earthquake magnitude. The parameter a depicts the measure of the level of seismicity while b is the ratio between small and large events such that a high b -value indicates a larger fraction of small earthquakes and vice versa. Schorlemmer et al. (2005) showed that the variation of the b -value is related to the fault mechanism and stress regime.

METHOD AND RESULTS

The KZN catalogue had 135 events and the one with the highest magnitude was $M_2 = 6.3$. Only Zones 3c and 3d as shown in figure 1 had sufficient data to reliably evaluate maximum magnitude via 60 and 33 events respectively. The level of completeness of the KZN catalogue was found to be $M_2 = 5$ (see figure 2) and was calculated using ZMAP Weimer (2001).

The theoretical background of the method applied in this study can be found in Kijko (2004) which is available in the Aki-Uwa Estimator programme Kijko and Smit (2012). This is a maximum likelihood procedure based on past seismicity that takes into account the various levels of completeness in the earthquake catalogue.

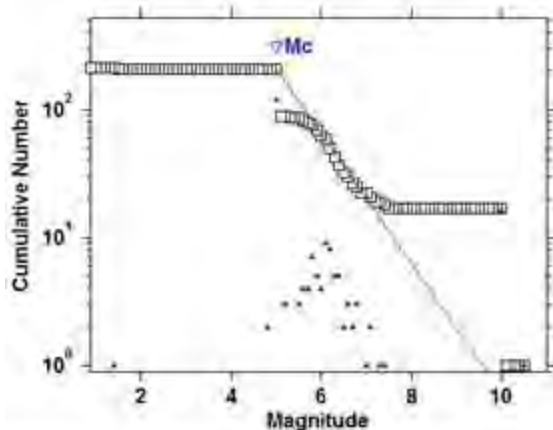


Figure 2. Level of completeness for KZN catalogue.

The seismic catalogue of KZN was divided into sections, the historical catalogue and the instrumental catalogue in order to account for varying levels of completeness. For Zone 3C the historical catalogue was for the period January 1967 to December 1985. The two instrumental catalogues were for the period January 1986 to December 2004 and January 2005 to December 2011 with 3.2, 2.2 and 1.5 as levels of completeness respectively (see figure 3a). For Zone 3D the historical catalogue was for the period January 1910 to December 1944 with a completeness of 3.7. The period of 1945-1989 was characterised by a lack of events. The two instrumental catalogues were for the period January 1990 to December 2004 and January 2005 to December 2011 with 2.7 and 1.5 as levels of completeness respectively (see figure 3b).



Figure 3a: Analysis of Zone 3C completeness with timescale.



Figure 3b: Analysis of Zone 3D completeness with timescale.

CONCLUSIONS

The maximum observed earthquake magnitudes (m_{max}^{obs}) for Zones 3c and 3d were $M_L = 5.6$ and $M_L = 4.4$ respectively. This is important as estimates of m_{max} are expected to be close to m_{max}^{obs} . Similar previous studies such as Shapira *et al.* (1989) and Singh (2009) yielded values of m_{max} that are different to the ones obtained in this study. This is because this value is largely dependent on the m_{max}^{obs} in the region and their studies were on a regional scale and therefore included $M_L = 6.5$ which follows outside of Zones 3C and 3D. The differences in activity rate and b-value are attributed to the fact that the zones used in this study are focused on smaller seismic units which has further altered the levels of completeness of catalogues whereas previous studies were on a larger regional scale.

ACKNOWLEDGMENTS

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