Understanding the seismicity and tectonic patterns along the east coast of South Africa using geophysical and geospatial techniques

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Submitted by:

Victor Philip Mapuranga

12213889

Supervisor: Professor Andrzej Kijko

Co-supervisor: Dr Mayshree Singh

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ABSTRACT:

The seismicity and seismotectonic setting of KwaZulu-Natal were studied using macroseismic data from two recent earthquakes in the province. It was shown that seismic activity is taking place along pre-existing zones of weakness which are currently undergoing reactivation. The earthquakes studied damaged low-cost houses more than well-built houses located in affluent suburbs, implying a greater need for strict enforcement of building codes relating to seismic loading in South Africa. An intensity-based attenuation relationship was calculated. It was shown that KwaZulu-Natal is vulnerable to tsunamis. Geophysical data was used to shed light on the crustal structure of KwaZulu-Natal. This produced 2.5D models of potential field data showing that the Natal Metamorphic Belt obducted northwards onto the southern margin of the Kaapvaal Craton where tectonic activity is still taking place. The approach of using 2.5D modelling of gravity and magnetic data applied in this study may serve as a benchmark procedure of seismogenic source delineation in South Africa.

KEYWORDS:

Seismicity; Seismotectonics; Macroseismic; KwaZulu-Natal

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DECLARATION:

I, the undersigned, declare that the thesis, which I hereby submit for the degree PhD Geology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution. I, the undersigned, furthermore, declare that:

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Full names:	Victor Philip Mapuranga
Student number:	12213889
Date submitted:	February 2023
Degree:	Ph.D. Geology
Topic of work:	*Understanding the seismicity and tectonic patterns along the east coast of South Africa using geophysical and geospatial techniques*
Supervisor(s):	Prof Andrzej Kijko, Department of Geology, University of Pretoria
Co-supervisor(s):	Dr Mayshree Singh, Land Surveying and Mapping Department, University of KwaZulu-Natal
Signature:	

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LIST OF ABBREVIATIONS

CGS - Council for Geoscience
EARS – East African Rift System
GDP – Gross Domestic Product
GMPE - Ground Motion Prediction Equation
GMM – Ground Motion Model
IAEA - International Atomic Energy Agency
IMS - International Monitoring System
ISC – International Seismological Centre
KZN – KwaZulu-Natal
MASW - Multichannel Analysis of Surface Waves
MM56 - Modified Mercalli Scale of 1956
NEIC - National Earthquake Information Centre
NMP – Natal Metamorphic Province
PSHA – Probabilistic Seismic Hazard Analysis
RDP - Reconstruction and Development Programme
SABS - South African Bureau of Standards
SANSN - South African National Seismograph Network
SCR – Stable Continental Region
UKZN – University of KwaZulu-Natal
USGS - United States Geological Survey

Chapter 1: Introduction

1.1 Introduction

The KwaZulu-Natal province of South Africa has recently undertaken several multibillion-rand infrastructural development projects. These include the Dube Trade Port, Port of Durban amongst others. The province boasts of well-developed transport and telecommunication systems. According to Statistics South Africa (2014) it is the second largest contributor to the South African Gross Domestic Product (GDP), after Gauteng province. These factors amongst others have enabled the province to support just under 20% of the nation's population (Statistics South Africa, 2019).

Earthquakes create seismic waves whose primary consequence is ground shaking. Secondary effects of earthquakes include phenomena such as soil liquefaction, tsunamis, landslides, and fires. The occurrence of a strong earthquake within the KwaZulu-Natal province and its neighbouring areas would have devastating effects on human lives as well as on the infrastructure that drives commerce and public health systems. To mitigate against these losses, it is pertinent that a carefully constrained and in-depth accurate study of the seismicity and tectonic patterns of the province be undertaken.

1.2 Rationale and problem definition

Historically, KwaZulu-Natal has experienced notable seismic events even though the monitoring of seismicity in the area has been sparse at best. Notable events include the 1932 earthquake of magnitude M_w=6.3 that occurred in the St Lucia area as well as the M_w=5.3 event in 1986 in Matatiele (Strasser and Mangongolo, 2013).The earthquakes mentioned above occurred at a time when the population of the region was relatively sparse compared with today. Settlement patterns in KwaZulu-Natal have since changed significantly, involving an increase in rural to urban migration. This has led to denser population settlements in areas like Durban and Pietermaritzburg.

Two earthquakes that occurred in relatively recent times raise interesting questions about the seismicity of KwaZulu-Natal. On 16 June 2015 an earthquake occurred in the Sundumbili region and was felt widely in the Zinkwazi area extending to Richards Bay. The United States Geological Survey (USGS) reported a magnitude of M_w=4.3 whereas the Council for Geoscience (CGS) reported a magnitude of M_L=3.8. According to Namole (2016), significant damage occurred near the Tugela River mouth to the local beach and a fishing spot which was a source of income and food to the local community. As in the 31 December 1932 earthquake which led to a tsunami, eyewitness reports said up to 100 m of beach area was flooded with water. This earthquake showed that KwaZulu-Natal is vulnerable to tsunamis and its location suggests possible reactivation of pre-existing zones of weakness at the boundary of the Kaapvaal Craton and Natal Metamorphic Province.

On the 6th of February 2016, another earthquake occurred off the coast of KwaZulu-Natal near Umhlanga and Durban north coastal areas. Preliminary macroseismic surveys conducted by the Council for Geoscience and the University of KwaZulu-Natal found damage to structures, particularly low-cost housing. There was controversy regarding the epicentre of this earthquake. According to the Council for Geoscience, the earthquake occurred 30 km offshore from Umhlanga whereas the United States Geological Survey reported that the epicentre was in Mpumalanga (near Hammarsdale – 60 km northwest from the Council for Geoscience epicentre. This uncertainty stems from a sparse seismic network for reliably monitoring earthquakes in KwaZulu-Natal which in turn leads to uncertainties about potential seismic sources.

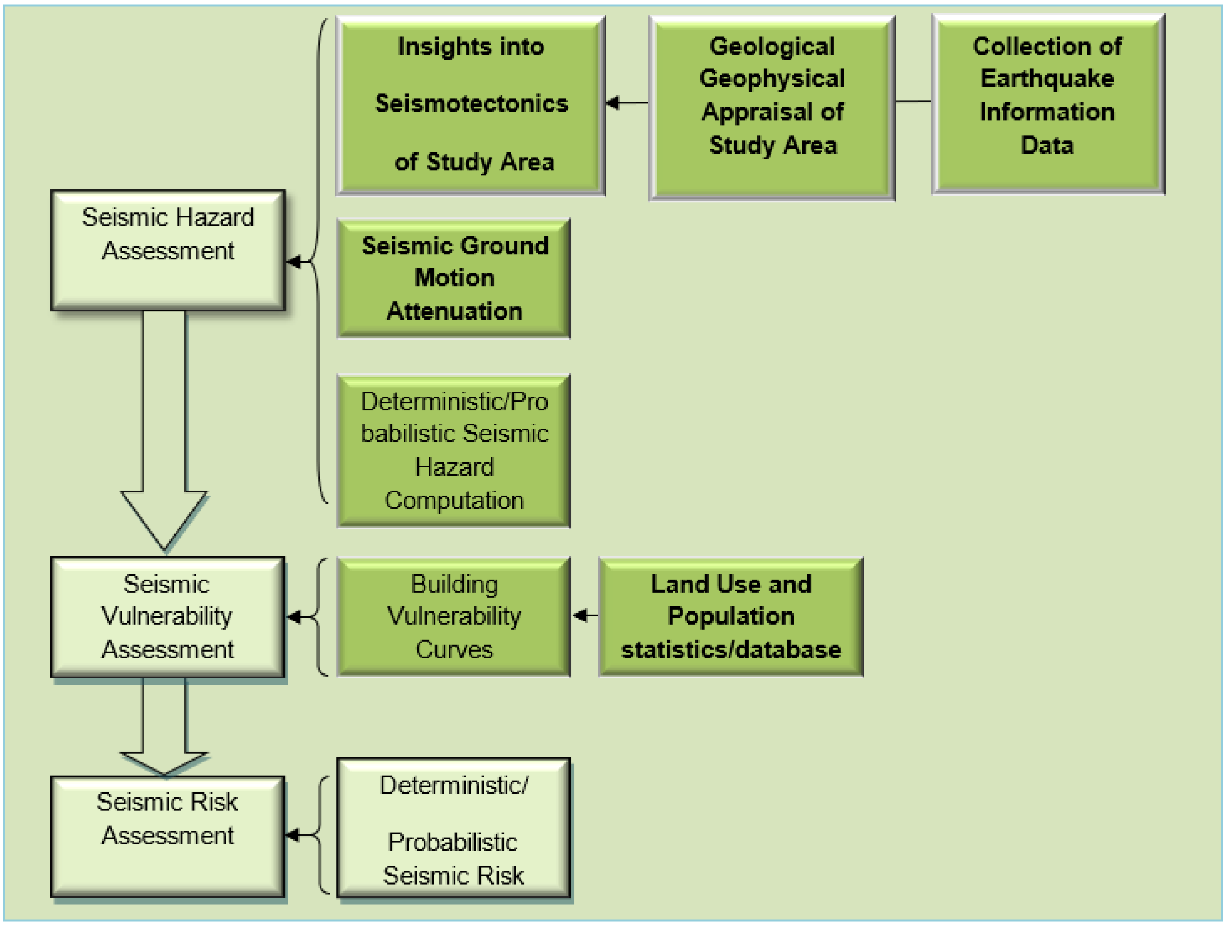

Figure 1.1 ***S****chematic representation of key components of seismic hazard and risk methodology providing context for the various component building blocks*

Singh (2016) carried out a regional seismotectonic study integrating multi-disciplinary geoscience data of KwaZulu-Natal. To build on this foundation, the data needs to be condensed and streamlined to distinct seismic sources. Constraining and understanding the seismicity to this level would contribute towards mitigating against loss of lives and destruction of infrastructure in the event of a strong earthquake occurring. This forms a key input component of seismic hazard analysis (Figure 1.1). The outputs of seismic hazard analysis are of valuable use to decision makers for disaster mitigation and land use planning, the insurance industry and seismic design codes for the engineering community.

1.3 Motivation

1.3.1 Improved seismic monitoring in the east coast

Seismic hazard analysis refers to the process of quantifying ground motion at a particular site. The ground motion is a result of earthquake occurrence and may result in ground shaking, landslides, tsunamis, liquefaction etc. (McGuire and Arabbasz, 1990). The primary aim of seismic hazard analysis is to mitigate against damage and losses that may result from the occurrence of earthquakes in the future. In recent years, Probabilistic Seismic Analysis (PSHA) has become the most standardised and principal procedure for seismic hazard analyses. The basic steps of PSHA as defined by Cornell (1968) have been refined over the years. Figure 1.2 below illustrates the steps for PSHA. This task may at times be complicated by unavoidable subjective decisions that have to be made based on incomplete and uncertain information (Kramer, 1996).

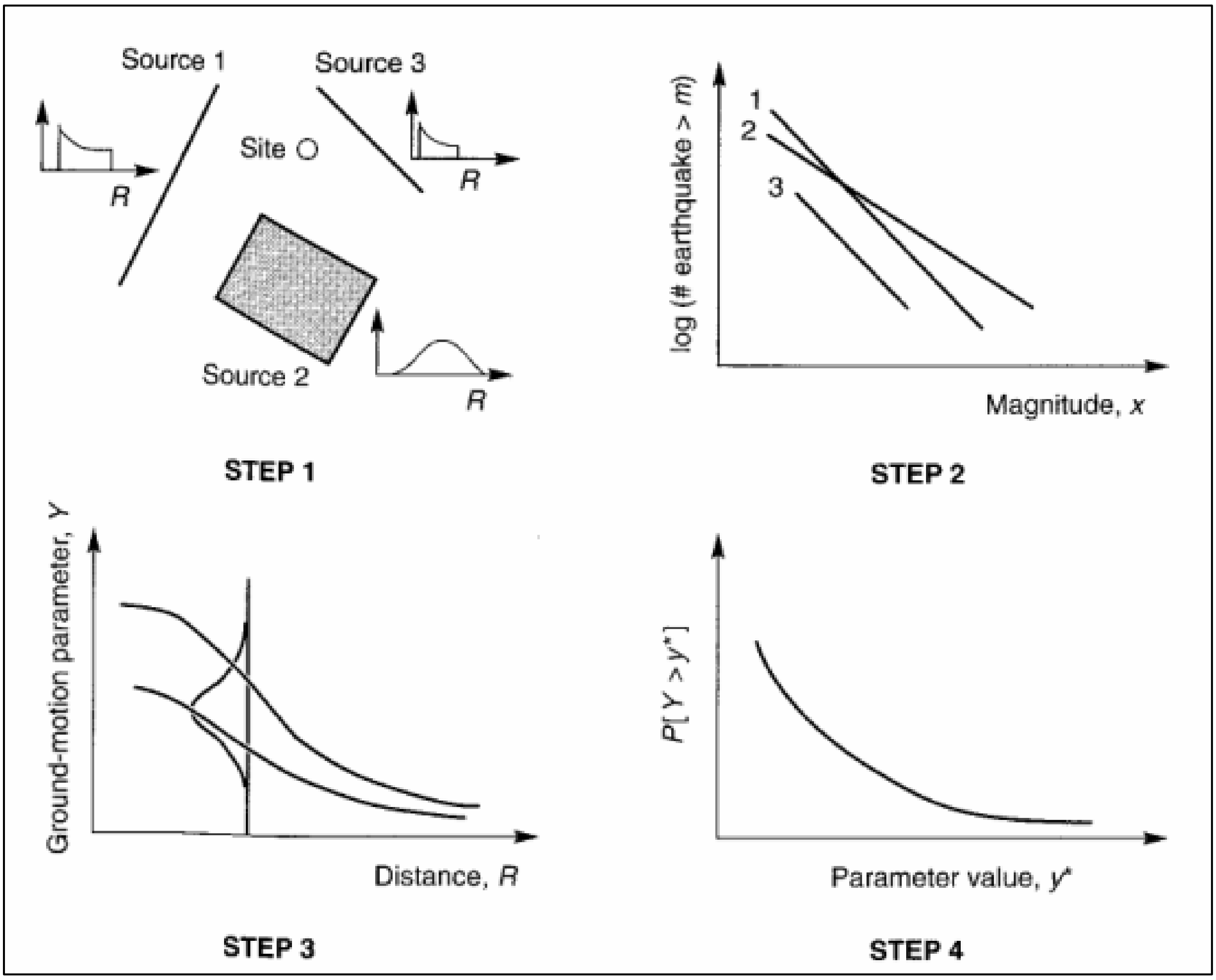

Figure 1.2 *Four steps of PSHA from Kramer (1996).*

The initial step of PSHA is the identification and delineation of seismic sources, which can generate earthquakes that may affect the site of interest. These sources could be faults, point sources or areal sources (Baker et al., 2021). Pre-instrumental and instrumental seismic information are routinely used as the first indicator of potential seismic sources (McGuire, 2004). Historical and pre-instrumental seismic information of South Africa is available from the Council for Geoscience. Singh et al. (2015) identified possible historical earthquakes in KwaZulu-Natal but paleoseismic studies are still required to identify more historical seismic events.

Presently, there are very few seismic monitoring stations in the province, and they are sparsely distributed. According to Saunders (2017), the minimum magnitude detection threshold for the South African National Seismograph Network (SANSN), which is maintained by the Council for Geoscience in KwaZulu-Natal, is M_L=3. This has led to the inability to detect critical micro-earthquakes whose epicentres are located on active structures, and poorly constrained source parameters for events that are detected. This results in poorly constrained seismic hazard analysis. Meghraoui et al. (2016) also bemoan this as a limiting factor in the identification and understanding the evolution of seismic sources for effective seismic hazard assessment.

Recently, there have been instances where social media was awash with reports of ground shaking in KwaZulu-Natal. The Council for Geoscience dismissed some of these reports as fake (Singh, 2021) but they leave one wondering, whether the current configuration of the SANSN might be unable to record significant micro-earthquakes that are occurring. The seismic sources of perceptible ground shaking effects that inhabitants of KwaZulu-Natal have observed could be a key input in seismic hazard analysis studies. Such macroseismic data is widely recognised as the oldest form of measuring earthquake size (Kramer, 1996). For regions that do not have strong motion records, macroseismic data can be also used to characterise earthquake effects and ground motion attenuation (Musson and Cecić, 2002; McGuire, 2004). This study aimed to shed some light on active seismic sources that have to be accounted for in seismic hazard analysis.

1.3.2 Lack of strong motion data in South Africa

Ground Motion Prediction Equations (GMPEs), also known as Ground Motion Models (GMM), are mathematical equations that provide a statistical prediction of the distributions of expected ground motion together with its standard deviation at a site, due to possible earthquake scenarios (Cotton et al., 2006; Edwards et al., 2016). The expected ground motion is usually defined in terms of magnitude, source to site distance, faulting mechanism, and site characteristics. GMPEs can be developed empirically from the regression of strong motion records or from simulated data.

Although an accelerometer network has been deployed in South Africa from 2012, no large magnitude events have yet been recorded and there is still a lack of records at near to intermediate distances (< 50 km) (Poggi et al., 2017; Midzi et al., 2020). It is standard practice in PSHA that a target region that lacks indigenous GMPEs adopts appropriate equations that have been developed for similar tectonic regimes. The task of selecting appropriate GMPEs is not to be taken lightly as the prediction of expected ground motion at a site is a major contributor to uncertainties in PSHA (Budnitz et al., 1997; Stepp et al., 2001).

Since macroseismic intensity is directly related to damage caused by earthquakes, it can be a reliable parameter for expressing seismic hazard (Slejko et al., 1998; Gómez-Capera et al., 2010; Cito et al., 2022). This can be particularly handy if strong motion data is unavailable. According to Musson and Cecić (2002), insurers and planners regard seismic hazard analysis that is expressed in the form of macroseismic intensity as preferable to ground motion parameters such as peak ground acceleration. For an engineering audience, macroseismic intensity based seismic hazard analysis can be converted to ground motion parameters (Faenza and Michelini, 2010; Gomez-Capera et al., 2020). Macroseismic intensity-based hazard maps have been used to test PSHA maps in places such as Japan and found to have good correlation (Miyazawa and Mori, 2009). These studies illustrate that for a country such as South Africa, where there is a lack of strong motion data, significant value can be extracted from macroseismic studies as a means of buttressing PSHA.

1.4 Aims and objectives

The goal of this research was to gain insights into the seismotectonics of the east coast of South Africa. Consequently, this will result in better constrained and reliable future seismic hazard analysis to mitigate against loss of lives and infrastructure when strong earthquakes occur. The following tasks were undertaken to achieve this goal:

1. To gain insights into the seismotectonics of the east coast through the macroseismic surveys of the 16 June 2015 and 6 February 2016 and KwaZulu-Natal earthquakes.
2. To define a local intensity attenuation model from macroseismic data.
3. To build a 2.5D model of the Natal Thrust Front from gravity and magnetic data to gain insights into the mechanism of seismic activity in this area.
4. To characterise the crustal structure of KwaZulu-Natal and how it influences seismicity along the east coast of South Africa.

1.5 Organisation of the thesis

Chapter 2 is a review of the seismotectonic setting of KwaZulu-Natal. The geology, seismicity and focal mechanisms of some earthquakes that have occurred in the province are discussed.

Chapter 3 is a macroseismic survey of the 6 February 2016 earthquake. The effects of the earthquake on low-cost housing and the controversy surrounding the epicentre of the earthquake are discussed. An attenuation model based on the macroseismic data from the earthquake is also defined.

Chapter 4 discusses the macroseismic survey of the 16 June 2015 earthquake whose epicentre was at the boundary of the Kaapvaal Craton and Natal Metamorphic Belt. The cause and possible mechanism of the earthquake is investigated within the context of the known geology, based on available gravity and magnetic data.

Chapter 5 discusses the crustal structure of KwaZulu-Natal. We highlight how previous research has been unable to include KwaZulu-Natal in studies of the crustal structure due to a lack of seismic stations in the province. We then use available gravity data to calculate the crustal thickness, seismic velocity, and density distribution in KwaZulu-Natal.

Chapter 6 summarises the key findings of this study and makes recommendations for future research.

Chapter 2: Review of the seismicity and geologic setting of KwaZulu-Natal

2.1 Introduction

South Africa has been described as a Stable Continental Region (SCR, i.e., intraplate region) that is characterised by low levels of seismicity (Johnston et al., 1994; Meghraoui et al., 2016; Manzunzu et al., 2019). This does not imply that it is completely rigid, but that deformation is very slow. According to Malservisi et al. (2013), South Africa has a strain rate of 1 nanostrain/year although the Cape Town region and KwaZulu-Natal exhibit higher strain rates. Intraplate earthquakes, particularly those in stable continental regions, typically have long recurrence intervals (Bodin, 2011). This lulls local inhabitants into being unprepared and so building vulnerable structures (Bodin, 2011). The M_w=6.5 Moiyabana event that occurred in south-east Botswana on the 3rd of April 2017 is a recent example of a potentially damaging intraplate earthquake in the region (Midzi et al., 2018; Mulabisana et al., 2021).

2.2 Geological setting of KwaZulu-Natal

2.2.1 Kaapvaal Craton and Natal Metamorphic Province

The rocks in the province are of Archaean (3.8-2.6 Ga) to Cenozoic (65 Ma – recent) age. A segment of the southern margin of the Archaean Kaapvaal Craton extends into northern KwaZulu-Natal (Figure 2.1). Together with the Natal Metamorphic Province, these form the foundational geological units of KwaZulu-Natal. The margin of the Natal Metamorphic Province is comprised of a granite-greenstone terrain (De Beer and Meyer, 1984).

The Proterozoic Natal Metamorphic Province flanks the southern margin of the Kaapvaal Craton and forms part of a Grenville orogenic belt (~1.1Ga) (Figure 2.1). According to Matthews (1972), the ophiolite assemblage of the Natal Metamorphic Province obducted northwards onto the southern margin of the Kaapvaal Craton. It extends laterally westwards into the Namaqua Province, through Natal and into Mozambique (Mendonidis and Graham, 2003; Mendonidis et al., 2015). Eglington et al. (1989) suggested that it was formed through juvenile accretion with subsequent differentiation. Thomas (1989) divided the Natal Metamorphic Province into three distinct tectonostratigraphic terranes, namely, from north to South: the Tugela, Mzumbe and Margate Terranes. The Lilani-Matigulu Shear zone separates the Tugela and Mzumbe Terranes while the Melville Shear Zone separates the Mzumbe and Margate Terranes.

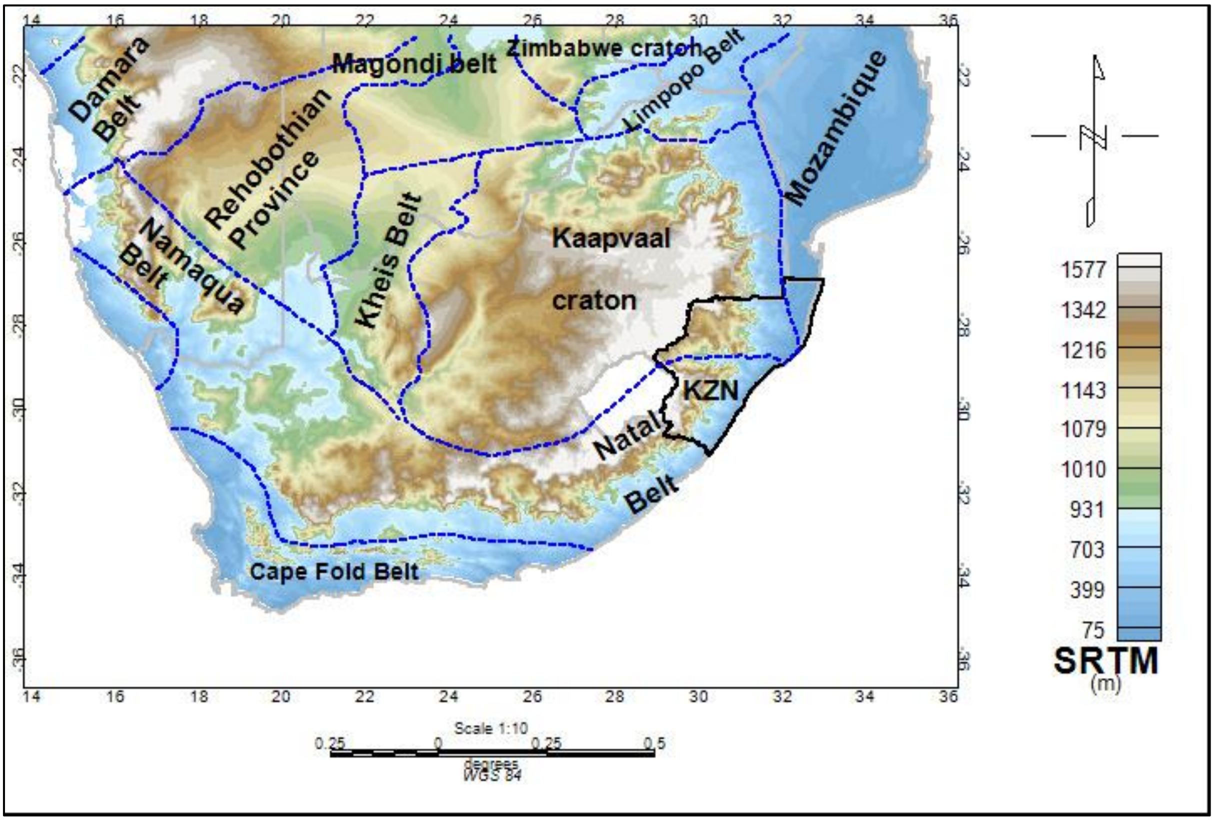

Figure 2.1 *Regional geological setting of southern Africa showing mobile belts and Archaean cratons modified from Corner and Durrheim (2018).*

The Tugela Terrane consists of a thrust sheet, representing a remnant of the Tugela Ocean. It has transported assemblages of mafic, ultramafic lavas and hypabyssal rocks (Thomas and Eglington, 1990; Mendonidis and Graham, 2003). In the south, the Mzumbe Terrane extends from south of Kranskop north to near Hibberdene. It is comprised of the Quha and Ndonyane Formations. The Quha Formation has the older rocks, which are amphibolite grade layered gneisses and migmatites while the younger rocks of the Ndonyane Formation are fine grained gneisses (Thomas, 1989; Clarke, 2008). The Margate Terrane mainly consists of granitoid gneiss and pyroxene gneisses. The Margate Terrane was thought to be a volcanic arc, but a recent study based on geological mapping and geochemical data suggests that it is rather a granitic batholith (Jacobs and Thomas, 1994; McCourt et al., 2006; Voordouw and Rajesh, 2012). The southern margin of the Natal Metamorphic Province is obscured by Phanerozoic sequences.

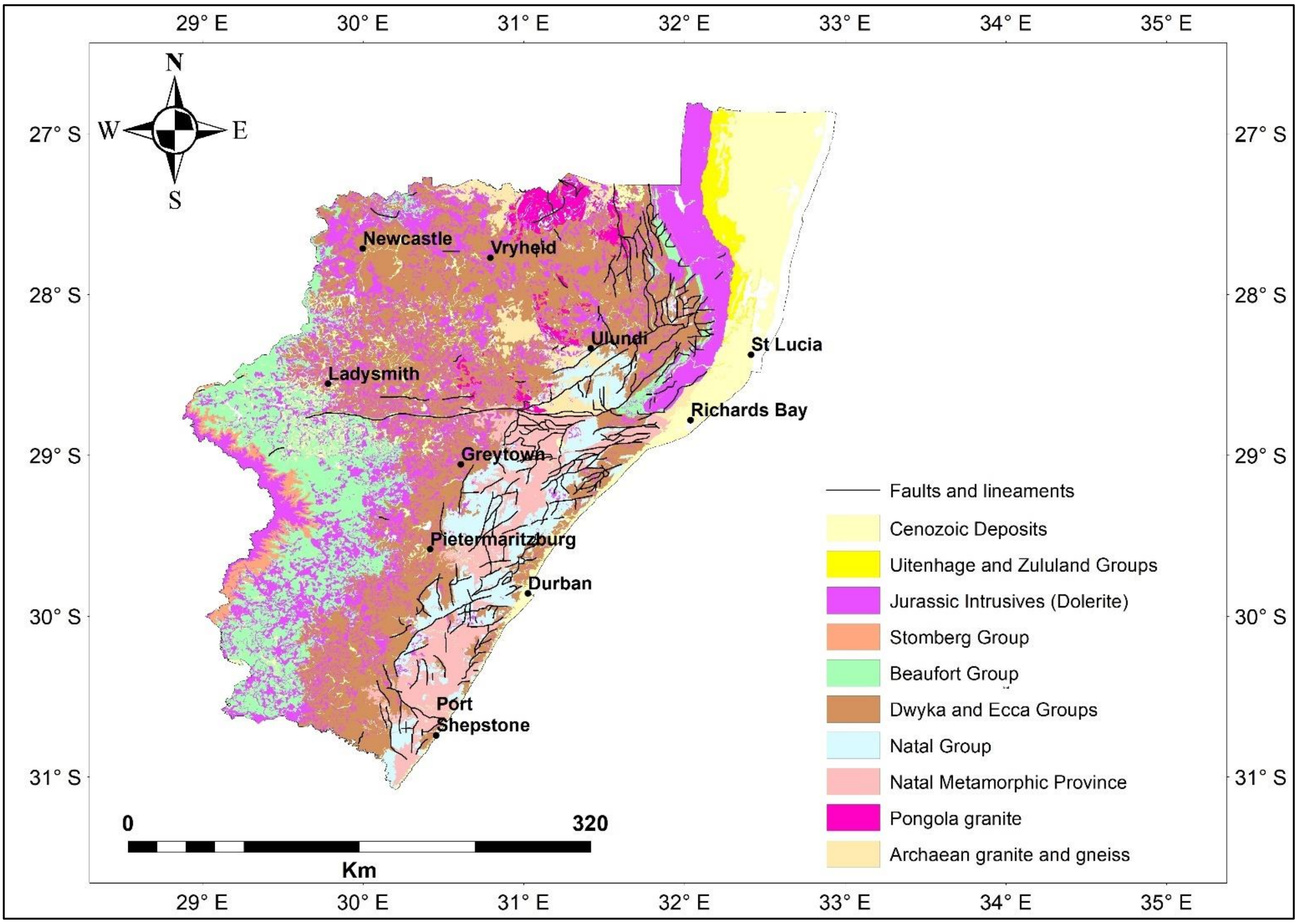

Figure 2.2 *Generalised geology of KwaZulu-Natal (data from Council for Geoscience).*

2.2.2 The Natal Group

The Natal Group is Ordovician (~490Ma) according to $^{40}Ar/^{39}Ar$ dating results of Thomas et al. (1992b). It lies to the east of KwaZulu-Natal and stretches from Ulundi in the north to Margate in the south. It consists of two formations which are approximately 600m thick. These are the lower Durban Formation as well as the upper Mariannhill Formation. The sedimentary rocks found in the Natal Group are greyish conglomerates, sandstones, siltstones and shales (Marshall and von Brunn, 1999; Hicks, 2010).

2.2.3 The Dwyka Group

The Palaeozoic Dwyka Group was deposited in southern Africa during the deglaciation of the Gondwana ice sheet. It is the lowermost unit of the Karoo Supergroup and constitutes its oldest rocks, extending from Late Carboniferous to Early Permian (Visser, 1989). It extends from Louwsburg in the north to Port St Johns in the south. According to Bangert and von Brunn (2001), the Dwyka Group consists of an assemblage of depositional sedimentary rocks which include diamictite, conglomerates, sandstones, siltstones and mudstones.

2.2.4 The Ecca Group

This group occupies most of the Permian time of the Karoo Supergroup and originates in post glacial, shallow marine, deltaic and fluvial settings which produced a complex stratigraphy (Bangert and von Brunn, 2001; Turner et al., 1981; Catuneanu et al., 2005). In the southern part of the main Karoo Basin, it attains its maximum thickness of 3000m. According to Catuneanu et al. (2005) in most of southern Africa the Ecca Group is consists of two or more formations. In KwaZulu-Natal, the more prominent formations are the Pietermaritzburg and Vryheid Formations which are dominated by sandstones together with mudrocks (Von Brunn, 1996).

2.2.4 Beaufort Group

This consists of fluvially deposited Late Permian-Triassic rocks that are found within the main Karoo basin making up 20% of the total surface cover of South Africa (Johnson et al., 1997). Deposition of the Beaufort Group occurred under semi-arid climatic conditions. The strata is predominantly mudstones and sandstones and they form the foothills of the Drakensberg Escarpment (Catuneanu et al., 2005).

2.2.5 Stormberg Group

The informal stratigraphic term “Stormberg” Group is commonly used in literature to refer to the uppermost sedimentary strata of the Karoo Supergroup (Johnson, 1994) and has thus been used herein as well. It is of Late Triassic to Early Jurassic age and lies on the uppermost part of the Karoo Supergroup around the Drakensberg Plateau, where it is well exposed. The Molteno, Elliot and Clarens Formations make up the Stormberg Group, with the Elliot Formation being underlain by the Molteno and overlain by the Clarens Formation (Bordy and Eriksson, 2015; Bordy et al., 2005). The Stormberg Group was deposited in a foresag setting formed in response to the final, first-order orogenic unloading of Pacific’s plate subduction underneath the Gondwana plate. It is dominated by sandstones and mudstones although siltstone and coal deposits also occur in less abundance (Catuneanu et al., 1998).

2.2.6 Drakensberg Group

Sedimentation of the Karoo Basin was finally terminated during the Early Jurassic by the outpouring of at least 1400 m of basaltic lava accompanied by the widespread intrusion of dolerite dykes and sills resulting in the Drakensberg Group. As a result, the Drakensberg Group is composed of basaltic volcanic rocks and felsic rhyolites overlying a sedimentary pile (Johnson et al., 1997; Nyathi, 2014). This volcanic occurrence was short and preceded the breakup of Gondwanaland.

2.2.7 Lebombo Group

This is a volcanic succession made up of thick basaltic lavas (Sabie River Formation) overlain by a succession of acid flow (Jozini Formation) that outcrops in Empangeni and extends 750 km northwards to the Limpopo belt (Saggerson and Bristow, 1983). Since it was involved in the 183 Ma Karoo event and the 135 Ma Cretaceous break up of Gondwana, the Lebombo Group can be regarded as a doubly rifted volcanic margin. The two events were followed by uplifting and faulting eventually resulting in the separation of Africa and Antarctica. The lithology of the Jozini and Sabie River Formations is made up of rhyolites, basalts with interbedded sandstones (Saggerson and Bristow, 1983; Watkeys, 2002).

2.2.8 Zululand Group

The Cretaceous Zululand Group is comprised of the Makatini, Mzinene and St Lucia Formations. It is well exposed on the western shores of St. Lucia, eastern Lebombo foothills, Phongola and Mkhuze River valleys (Kennedy and Klinger, 1975). According to Dingle et al. (1983) these three formations consist of conglomerates, sandstones, siltstones and limestones.

2.2.9 Cenozoic sediments

Cretaceous to Cenozoic Era sediments form a thin covering that overlies the Zululand Group along the northern KwaZulu-Natal coastline (Dingle et al., 1983). According to Roberts et al. (2006) and Shone (2006) these deposits initially developed as a result of marine transgressions and regressions related to the breakup of Gondwana. Sea level fluctuations concomitant with world-wide climatic changes are also thought to have played a crucial role in the formation of large dune complexes that can be seen parallel to the coastline. Formations here consist of thin basal conglomerates, limestones, thin lenses of clay, fossiliferous silts and shallow marine sands (Wright et al., 2000).

2.3 Seismicity of KwaZulu-Natal

The Council for Geoscience are the custodians of the South African National Seismograph Network which monitors earthquake occurrences in South Africa. Most seismic activity that occurs in South Africa is mining related. Therefore the configuration of the South African National Seismograph Network is biased towards the detection of induced seismicity (Shapira et al., 1987). The instrumental (post 1970) seismicity of KwaZulu-Natal was recently well documented by Saunders (2017). The historic catalogue (pre-1970) is available from the Council for Geoscience and was updated by Singh et al. (2015) who found undocumented historical earthquakes to supplement the Council for Geoscience’s historical catalogue.

Some seismic clusters can be observed on the seismicity map shown as Figure 2.3. Cluster A is related to induced events from coal mining at Ermelo and Klip River. Cluster B is caused by reservoir induced seismicity at the Drakensberg Pumped Storage Scheme. This is a hydroelectric power station that comprises four dams constructed between 1974 and 1982. According to Saunders (2017), fourteen reservoir induced events were recorded within cluster B between October 2008 and November 2012.

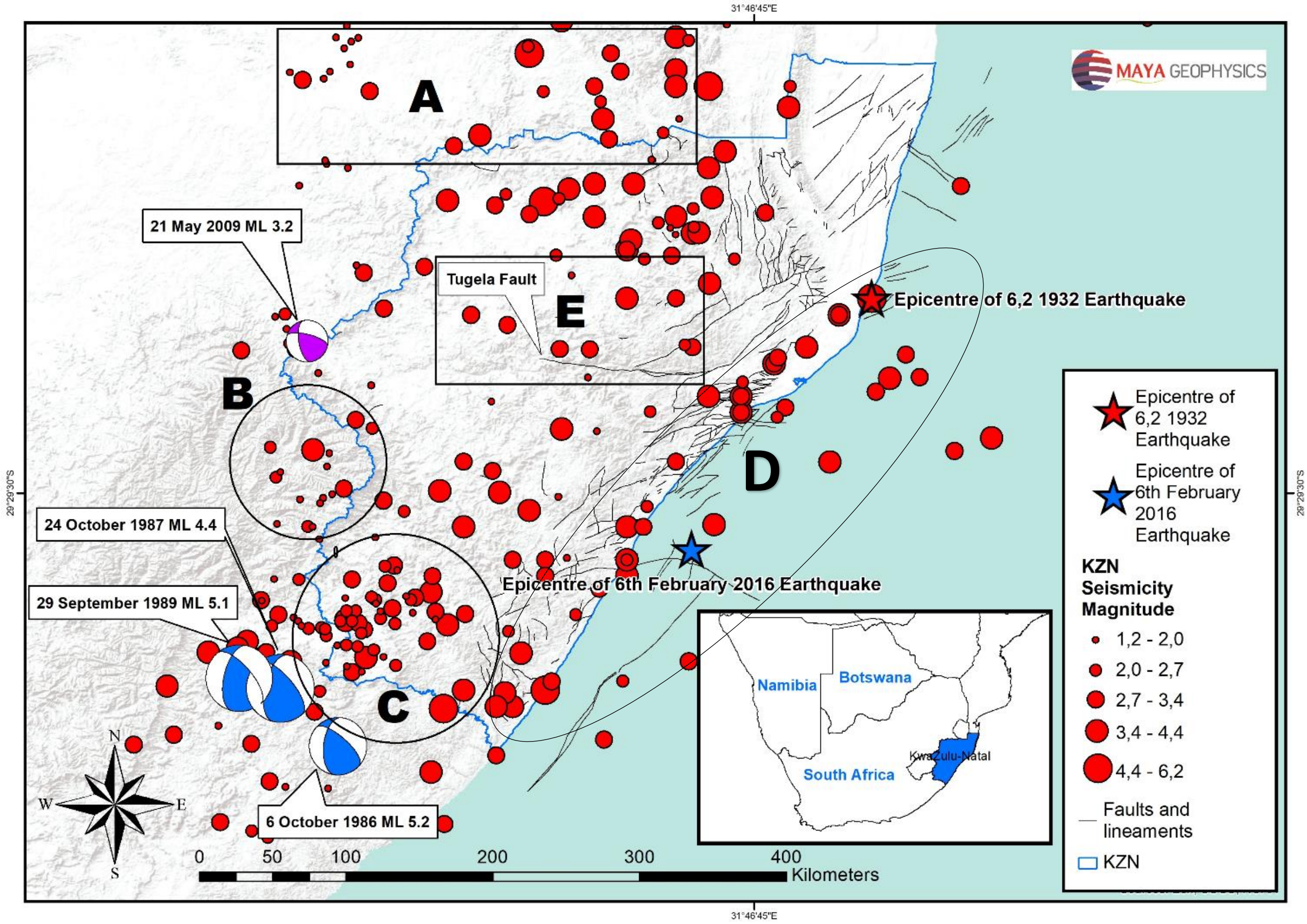

Figure 2.3 *Seismicity map of KwaZulu-Natal superimposed on fault lineaments in the province. Focal mechanisms of selected events represented by blue and purple beach balls denoting normal and reverse faulting, respectively.*

Cluster C coincides with the east-west trending active Cedarville fault near Matatiele and in Lesotho. This area is characterised by small to moderate sized events (Strasser and Mangongolo, 2013; Manzunzu et al., 2019). The largest earthquake in this area was the 6 October 1986 M_w=5.2 event. This area may be an example of “hotspot pre-weakening”, signifying the southwest extension of the East African Rift System (EARS) into South Africa (Hartnady, 1985; Brandt, 2011).

Another distinguishable set of seismic activity trends in a NE-SW pattern parallel to the coast together with activity at the Natal Thrust Front. According Watkeys and Sokoutis (1998a), the NE-SW faults are related to the Gondwana break up which still continues to this day. The Natal Thrust

Front coincides with the southern margin of the Kaapvaal Craton and is the boundary between the Tugela and Margate Terranes. It is the site of hot springs, and it has also been reported as the site of a minor volcanic eruption. It also coincides with the neotectonic Quathlamba seismicity hotspot presently located at ~30°S and ~29°E (Gevers, 1963; Hartnady, 1990; Jacobs and Thomas, 1994). This suggests that tectonic activity along this zone is still happening.

2.4 Geological fault patterns in KwaZulu-Natal

The coastal region of KwaZulu-Natal has a distinct zone of complex faulting associated with crustal extension that was instigated by the Mesozoic break up of Gondwana. Several authors e.g., (Maud, 1961; von Veh and Andersen, 1990; Watkeys and Sokoutis, 1998a) have described the coastal faulting in KwaZulu-Natal (Figure 2.3). Regions of Archaean basement exhibit a different style of faulting in comparison to Proterozoic basement localities. The Archaean regions show extension normal to the proto-plate boundary whereas transtension is prevalent in Proterozoic regions. von Veh and Andersen (1990) and Singh (2016) suggested that there are three major fault trends in KwaZulu-Natal. These are the NE-SW coast parallel patterns, arcuate patterns in the southeast, and NW-SE coast perpendicular orientations in the north. The arcuate faults are progressively younger towards the south.

2.4.1 NW-SE coastal perpendicular orientations in the north

These faults exhibit north-south trends that are characterised by a series of horsts and grabens (Watkeys and Sokoutis, 1998b). For example, the Mlalazi Fault extends in a westerly direction cutting across the Mlalazi River valley and marks the down faulted boundary of the Ngoye horst. Using aeromagnetic data and an abrupt change in stratigraphy, von Veh and Andersen (1990) also inferred the Gingindlovu Fault and another at Mtunzini which are of comparable trend. The Gingindlovu Fault marks the northern boundary that has Ecca Group sediments against Natal Group sandstones.

The Nembe Fault located fifty kilometres north of the contact with the Natal Metamorphic Province marks a region where the trend of north-south faults changes. It has a northeast trend for most of its length. At the eastern end, the Nembe Fault trends in a southeast ward where it terminates at the Nyezane Fault which trends east-west, effectively joining it with the north-south trending faults. East-west trending faults like the Nyezane Fault separate the Archaean Kaapvaal Craton from the Proterozoic Natal Metamorphic Province (von Veh and Andersen, 1990; Watkeys and Sokoutis, 1998a)

2.4.2 The arcuate fault patterns in the southeast and NE-SW trends parallel to the coast

Watkeys (2002) provided a framework of prolonged tectonic history subdivided into five phases that resulted in the Gondwana break-up. In the fourth phase (135-115 Ma), the Falkland Plateau was extracted from the Natal Valley. This is generally accepted as the cause of the coastal faulting in KwaZulu-Natal which is associated with dextral strike-slip movement. According to Thomas (1988) the zone of coastal faulting that lies north of Durban is 70km wide. Fault traces in this region are bow-shaped and change from ENE-WSW strike to a north-south trend. The cause of this pattern is unknown as the area is not well exposed and experiences sub-tropical weathering. These faults are listric normal faults convex towards the coast and have been reactivated a number of times in addition to being active in some places (Watkeys and Sokoutis, 1998a) .

Discriminating whether a fault is active or inactive is a challenge that divides opinions amongst researchers and regulatory bodies. Toda (2011) defined an active fault as one that is likely to cause a large earthquake in the near future or one that is associated with tectonically deformed Quaternary-age material. If no current activity is recorded along the length of a fault, then determining whether the fault is active or not is based on the age of the youngest observed deformation (Marshak, 2013; Jomard et al., 2017). Meghraoui et al. (2016) defined the age of these deformations as the middle Pleistocene.

Regulatory bodies apply different temporal limits to the description of active faults. For example, the International Atomic Energy Agency requires that for intraplate regions, capable faults should be analysed by collecting geological information covering the Plio-Quaternary period (IAEA, 2010). On the other hand the United States Nuclear Regulatory Commission (2017), defines a capable fault as one that has exhibited movement at least once in the past 35 000 years, or movement of a recurring nature in the past 500 000 years. Alternatively, according to US Nuclear Regulatory Commission (2017), a fault may be considered as active if instrumental macro seismicity of sufficient precision can be directly attributed to that fault.

In KwaZulu-Natal it is difficult to identify actual fault sources of seismic events as the earthquake magnitudes are small to moderate and therefore do not rupture the surface. Also, the sparsity of the seismic network in the province means that earthquakes are not located with sufficient precision. This challenge has been noted in a related study by Midzi et al. (2016). Therefore, active faults identified in this study have been digitised from published and unpublished reports and have been identified as being favourably oriented with respect to the regional stress field (Singh, 2016). The data pertains to investigations of the near regional area relating to stratigraphy, structural geology and tectonic history as outlined in the International Atomic Energy Agency guidelines (IAEA, 2010).

The exact age of inland faults is not known with certainty. However based on truncation relationships of the faults from aeromagnetic data and resistivity data there is a general consensus that faults parallel to the coast and cutting the Zululand Group north of Mthunzini can be constrained to be of

Cretaceous timing (von Veh, 1994; Watkeys and Sokoutis, 1998a). One example of this is the Hyde Park Fault that cuts through the Zinkwazi and Umvoti Faults.

2.5 Focal mechanism solutions and regional stress field of KwaZulu-Natal

It is common practice for the inversion of focal mechanisms to be used for better understanding of the stress field (Delvaux and Barth, 2010; Maury et al., 2013; Sheikholeslami et al., 2021). Since KwaZulu-Natal has not had many instrumentally recorded earthquakes with a magnitude greater than 5, only the 5 October 1986 Mw=5.2 earthquake is included in the Global Centroid Moment Tensor Catalogue (Dziewonski and Woodhouse, 1983; Ekström et al., 2012). The solution for the earthquake indicates normal faulting. Saunders (2017), was able to calculate the fault plane solution of the earthquakes shown in Figure 2.3. The focal mechanisms showed normal faulting in southern KwaZulu-Natal whereas the 21 May 2009 M_L=3.2 event near Phuthaditjaba indicates reverse faulting. Most recently, Manzunzu (2021) analysed 175 focal mechanisms across South Africa. The trend of the stress pattern was dominated by NE- to ENE-oriented trends with solutions from KwaZulu-Natal showing a normal faulting regime and it was concluded that the rate of deformation is too slow to be able to reliable associate seismic events with particular faults.

2.6 Conclusion

Although KwaZulu-Natal is characterised by high deformation rates compared to most of South Africa, these rates are relatively small when compared to active tectonic regions such as the East African Rift System. The seismicity patterns of the province may be correlated to geological structures such as the Tugela fault while some seismic events are due to anthropogenic activity such as mining and the Drakensberg Pumped Storage Scheme. The stress patterns in the region have also been attributed to the southward propagation of the East African System into southern Africa contributed to the reactivation of pre-existing zones of weakness (Fairhead and Henderson, 1977; Scholz et al., 1976; Partridge, 1995).

Chapter 3: Macroseismic survey of the 6 February 2016 KwaZulu-Natal, South Africa earthquake

The contents of this chapter were published in:

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Abstract

On the 6th of February 2016 at 1100 hours local time (0900 UTC), KwaZulu-Natal was struck by an earthquake of local magnitude M_L=3.8. The epicentre of the earthquake was located offshore in the Durban Basin. The earthquake shaking was widely felt within the province as well as in East London in the Eastern Cape Province and was reported by various national media outlets. Minor structural damage was reported. A macroseismic survey using questionnaires was conducted by the Council for Geoscience (CGS) in collaboration with the University of KwaZulu-Natal (UKZN) which yielded 41 intensity data points. Additional intensity data points were obtained from the United States Geological Survey (USGS) *Did You Feel It?* programme. An attempt was made to define a local intensity attenuation model. Generally, the earthquake was more strongly felt in low-cost housing neighbourhoods than in more affluent suburbs.

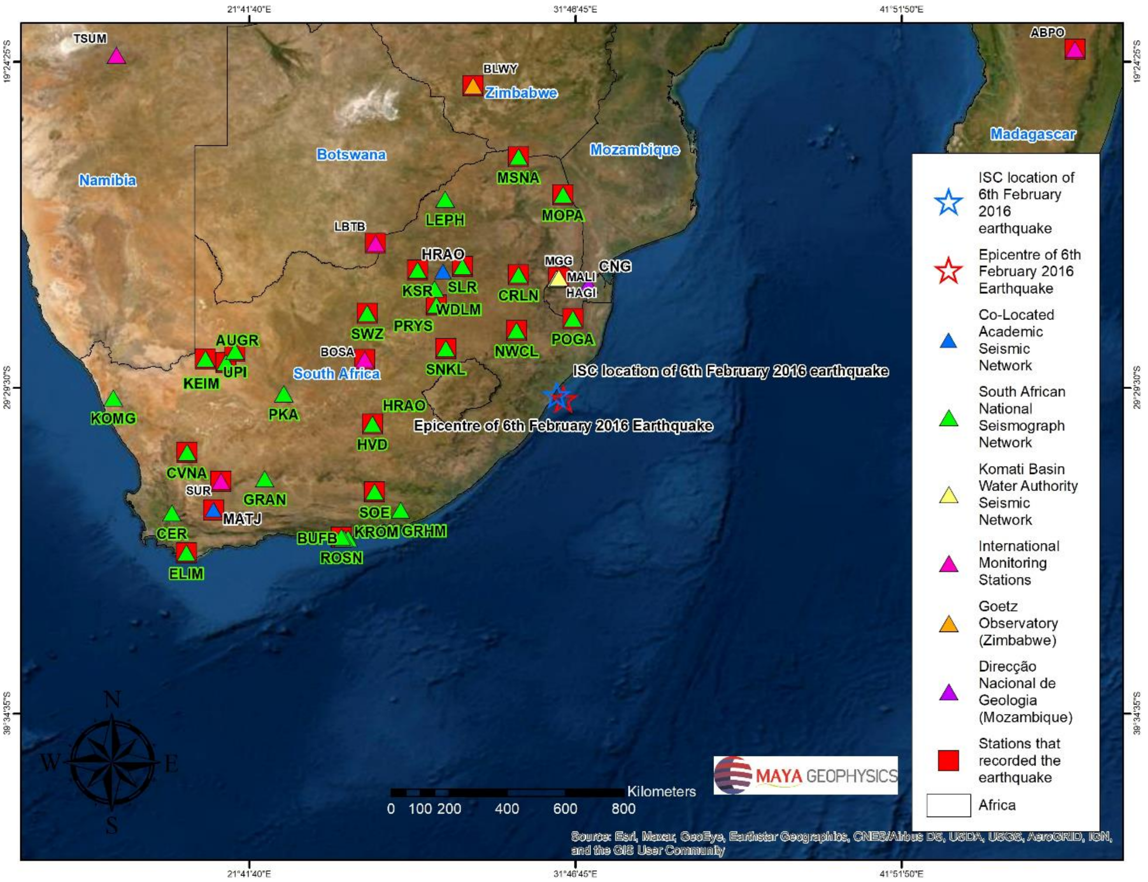
Keywords: Intensity Data Point, KwaZulu-Natal, Macroseismic survey, Offshore

3.1 Introduction

On the 6th of February 2016 at 1100 local time (0900 UTC), KwaZulu-Natal Province was struck by an earthquake of local magnitude M_L=3.8. Using the network of local South African National Seismograph Network (SANSN) and International Monitoring System (IMS) seismic stations, the earthquake was located offshore at 29.864° S and 31.329° E. The error ellipse of the location was found to be ±2.5 km and ±3.9 km in the major and minor axis, respectively. Since the hypocentral depth would have been unreliable at regional distances recorded with a sparse seismic network, the depth of the event was fixed at 6 km based on the work of Saunders (2017), who concluded that the majority of events in KwaZulu-Natal occur at this depth using synthetic waveform modelling. No aftershocks were identified after this event.

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

The USGS National Earthquake Information Centre (NEIC) also reported this event with body wave magnitude m_b=3.7 but with an onshore location at 29.552° S and 30.729° E using phase information from seven regional seismic stations. This prompted the need to re-analyse the earthquake location using local SANSN and regional phase information that had not been considered initially (Figure 3.1).



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

***Figure 3.1** The analysed (red star) and ISC (blue star) epicentre of the 6 February 2016 event and seismic stations.*

The event was re-analysed using the HYPOCENTER computer code (Lienert and Havskov, 1995) which uses a damped least-squares procedure to iteratively solve the travel-time equation. The International Seismological Centre reviewed bulletin (ISC, 2021; Di Giacomo et al., 2014) location shown in Figure 3.1 also provided additional confirmation that the epicentre of this event was offshore and had incorrectly been located by NEIC.

The earthquake was felt widely in KwaZulu-Natal as well as East London in the Eastern Cape Province and was reported by various national media outlets. A macroseismic survey was conducted by the Council for Geoscience in conjunction with the University of KwaZulu-Natal. People in low-cost housing felt the shaking more strongly than people in the more affluent areas, such as Umhlanga Rocks, which were much closer to the epicentre. Amanzimtoti, Hammarsdale and Umhlanga Rocks are located 50 km, 84 km, and 30 km from the epicentre respectively. Minor structural damage was reported in low-cost houses at Hammarsdale while a long hairline crack in the floor tiles was also observed at the Hammarsdale Junction shopping centre (Figure 3.2a).

***Figure 3.2** Structural damage resulting from the 6 February 2016 KwaZulu-Natal offshore earthquake (a) Long hairline crack at the Vodacom store, Hammarsdale mall, (b) Damage to a government subsidised Reconstruction and Development Programme (RDP) home in Hammarsdale*

3.2 Seismic history of KwaZulu-Natal

KwaZulu-Natal is characterised by moderate levels of seismicity with several earthquake epicentres located along the KwaZulu-Natal NE-SW coastal faults (Figure 3.3). This suggests a relationship between epicentres and lineaments, although some events can be observed that cannot be correlated to any known lineaments. Focal mechanisms obtained by Saunders (2017) show normal faulting in southern KwaZulu-Natal, whereas the 21 May 2009 M_L=3.2 event near Phuthaditjaba indicates reverse faulting.

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

Instrumental seismicity of the province may be correlated to pre-existing zones of weakness. Several faults that originated from the Gondwana breakup approximately 180 million years ago, lie along the coast with a NW-SE trend (Maud, 1961; von Veh, 1994). The north of the province is typified by NW-SE faults perpendicular to the coast and characterised by a series of horsts and grabens (Watkeys and Sokoutis, 1998a). A prominent active fault in the province is the E-W oriented Tugela fault (Figure 3.3). Several thermal springs and carbon dioxide exhalation sites are located along this fault indicating neotectonic activity (Hartnady, 1985; Johnson et al., 2017).

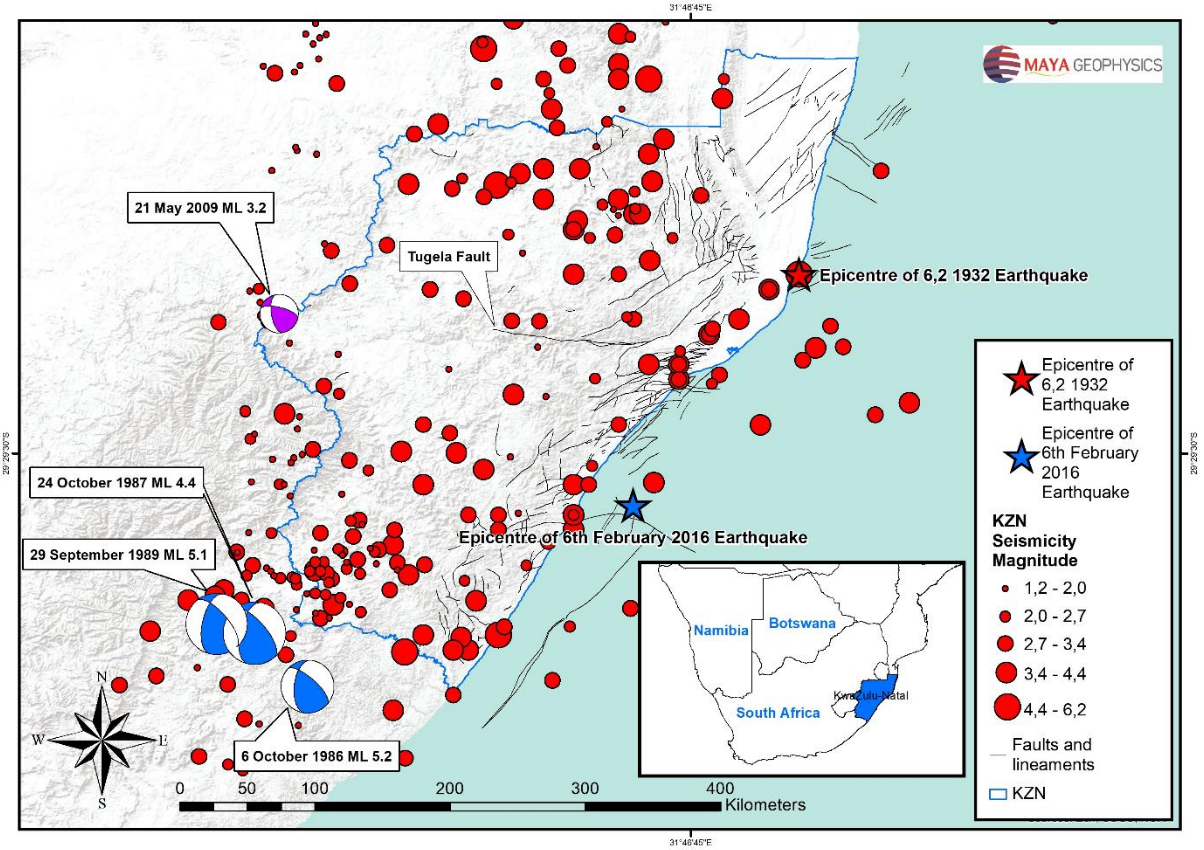


Figure 3.3 *Seismicity of KwaZulu-Natal superimposed on fault lineaments in the province. Focal mechanisms of selected events represented by blue and purple beach balls denoting normal and reverse faulting, respectively.*

Singh (2016) stated that the significant number of historical events that were reported along the coast may be attributed to historical population patterns where more communities settled in these areas in comparison to those that settled inland. Presently, there are very few seismic monitoring stations in the province, and they are sparsely distributed, as seen in Figure 3.1. According to Saunders (2017), the minimum magnitude detection threshold for SANSN in KwaZulu-Natal is M_L=3. This has resulted in the inability to detect critical micro-earthquakes whose epicentres are located on active structures, and in poorly constrained source parameters for events that are detected.

3.3 Intensity scales

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

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

3.4 Macroseismic survey and data analysis

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

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

Due to limited financial and human resources, the data collected from field surveys were limited and collected only from suburbs of Durban and Hammarsdale. To augment this dataset, a decision was made to include online information obtained from the United States Geological Survey's (USGS)

”*Did You Feel It?*” programme (Wald et al., 2012). The USGS collected 24 observations from seven suburbs. It should be noted that the USGS does not disclose individual responses but provides an aggregated intensity summary information for each location (Table 3.1).

3.5 Observations and intensity data points (IDPs)

The procedure of Musson and Cecić (2002) was followed in rendering the observations from the questionnaires into intensity data points. This procedure requires that the seismologist gathers available information and therefore it follows that there will be increased confidence in areas with more observations. The initial step was to systematically catalogue the observed data from questionnaires according to the suburb or district it was captured from. The number of observations captured from each suburb or district during the local survey is represented in blue in Figure 3.4 while USGS observations are indicated in red.

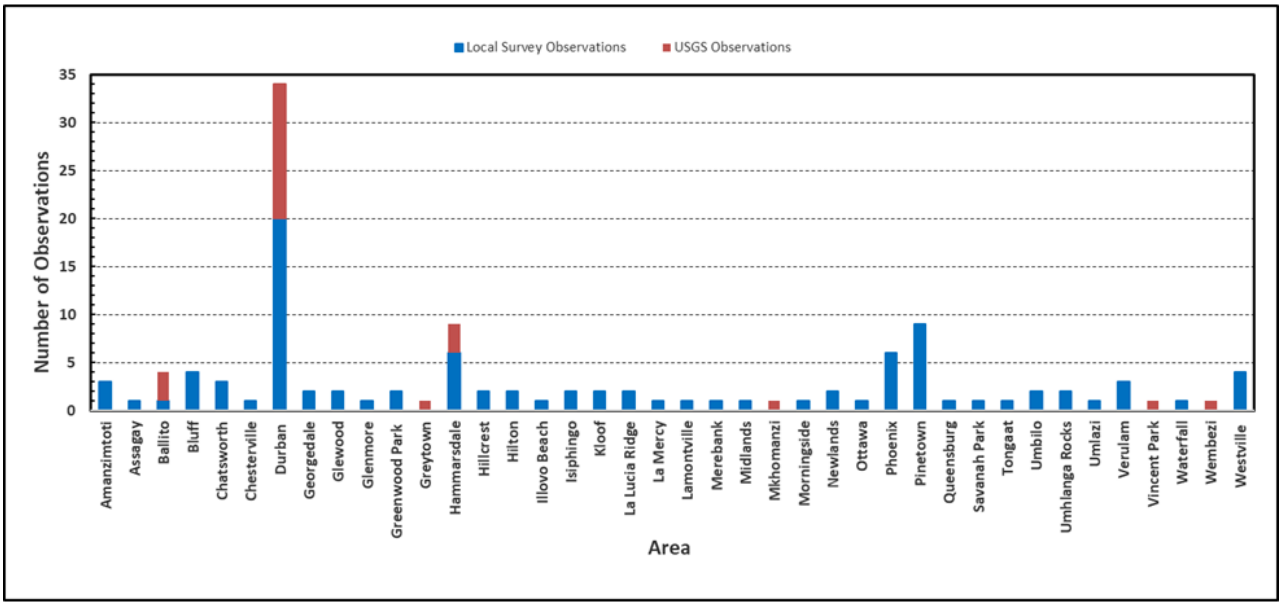


Figure 3.4 *The number of observations used to create each data point divided into areas*.

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

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

Table 3.1. *Responses obtained from the USGS "Did You Feel It" programme.*

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

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

The largest number of intensity data points had an intensity level of III. Levels III-IV and IV had one and two intensity data points respectively. The number of intensity data points obtained for each intensity level is shown in Figure 3.5 while their spatial distribution is shown in Figure 3.6. The highest level of intensity (V) was observed at Ballito and Hammarsdale which are located at epicentral distances of approximately 34km and 79km, respectively. The level of intensity that is felt during an earthquake depends on the magnitude, location, and epicentral depth and overlying soil conditions.

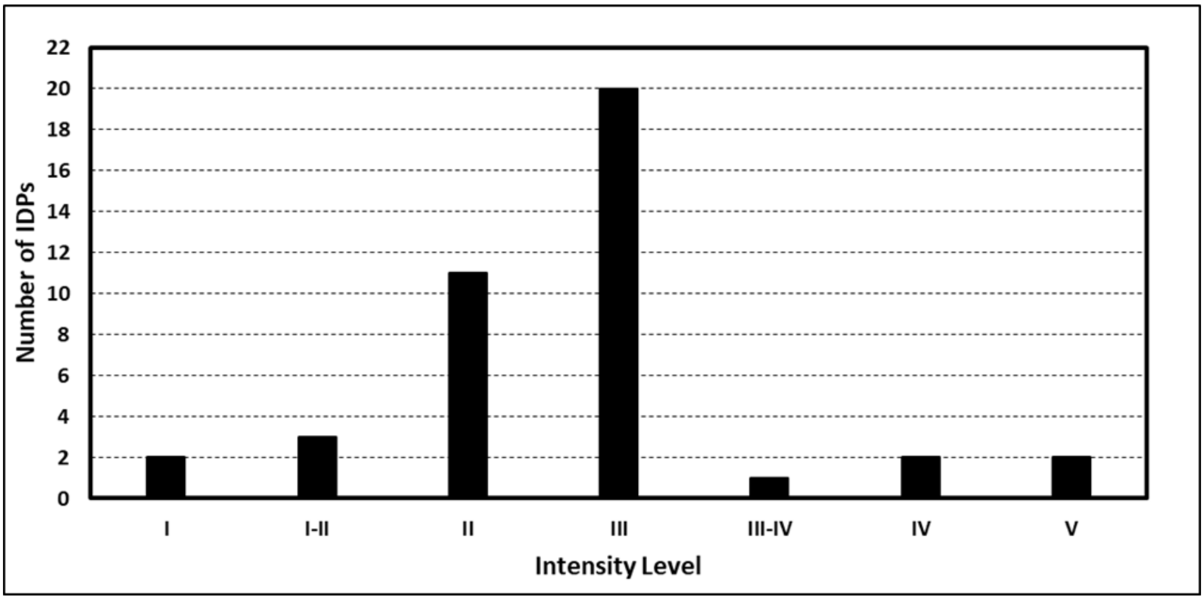


__Figure 3.5__ The number of intensity data points obtained for each intensity level.

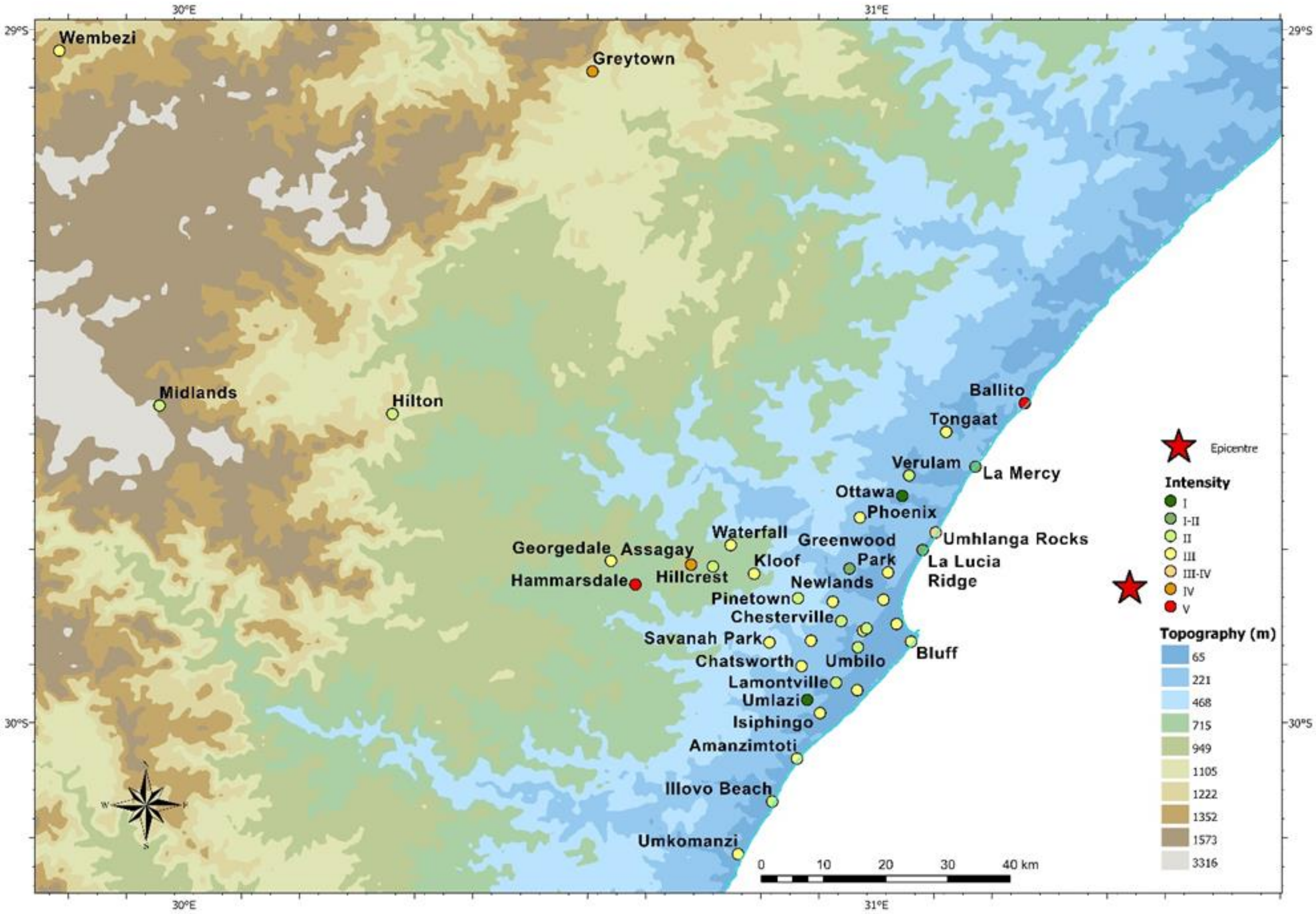


***Figure 3.6** Spatial distribution of intensity data points superimposed on the topography of KwaZulu-Natal.*

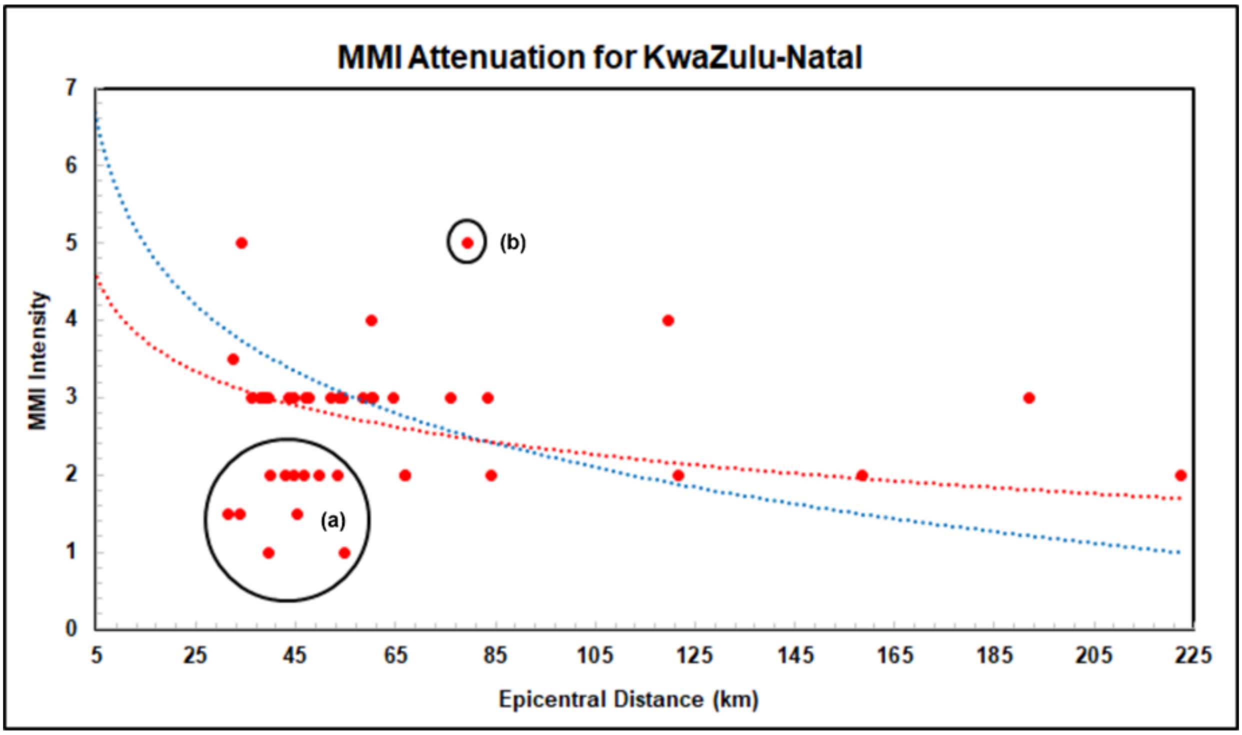


Figure 3.7 *The intensity–distance plot for the intensity data points obtained for the 6 February 2016 KwaZulu-Natal earthquake. The blue dashed line represents the modified Bakun and Scotti (2006) and the red dashed line represents the new intensity-distance attenuation model. Anomalous data points (a) and (b) are discussed below.*

The distribution of intensity with epicentral distance was plotted (Figure 3.7) to gain an understanding of the attenuation of seismic waves in the region. An attempt was made to define a local intensity attenuation relation, which we compared to the model of Bakun and Scotti (2006) for the French stable continental region as South Africa has also been described as a stable continental region (Johnston et al., 1994)

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

$$I_0 - I = -a_1 - a_2 In\, R - a_3 R \qquad (3.1)$$

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

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

$$I_0 = \tfrac{3}{2}M - 1 \qquad (3.2)$$

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

Our model is given by:

$$I = 0.93 + 1.27M - 1.73log_{10}\,(R) \qquad (3.3)$$

The newly developed relationship appears to display a bias in attempting to fit both low and high-intensity values, which may be a result of local site effects. The cluster of intensity data points labelled (a) in Figure 3.7, would have been expected to exhibit higher intensities as they are located relatively close to the epicentre at 30 to 60 km. Upon closer inspection, most of these intensity data points are in affluent suburbs such as La Lucia, Hillcrest and Glenwood, with well-built housing. It is therefore sensible that the effects of the earthquake would have been felt to a lesser extent than in (b) which is in Hammarsdale. Some of the observations in Hammarsdale which resulted in structural damage (see (b) of Figure 3.2) are from poorly built houses and therefore it is unsurprising that this resulted in structural damage even though they were located further from the epicentre.

3.6 Isoseismal map

Geostatistical methods, which include the natural neighbour and Kriging techniques, have been used in attempts to produce objective isoseismal maps (Sirovich et al., 2002; Schenková et al., 2007). According to Tily and Brace (2006), the natural neighbour technique is most suitable for the interpolation of irregularly distributed data, which are dense in some areas and sparse in others. As can be observed in Figure 3.6, the intensity data points in this study are tightly clustered in the near-field of the epicentre and scattered in the far-field, therefore this dataset was deemed to be suitable for interpolation using the natural neighbour technique.

The resulting isoseismal map is shown in Figure 3.8 below. The warmer colours represent higher levels of intensity as indicated in the map legend. The greatest levels of intensity (IV and V) can be observed towards the north in Hammarsdale, Assagay, Ballito and Greytown. Coastal areas that are much closer to the epicentre such as Umhlanga Rocks, Durban, and Bluff, interestingly were amongst some of the areas where moderate levels of intensity III were recorded. The lowest intensity levels (I to II) were observed in Hilton, Midlands and Hillcrest.

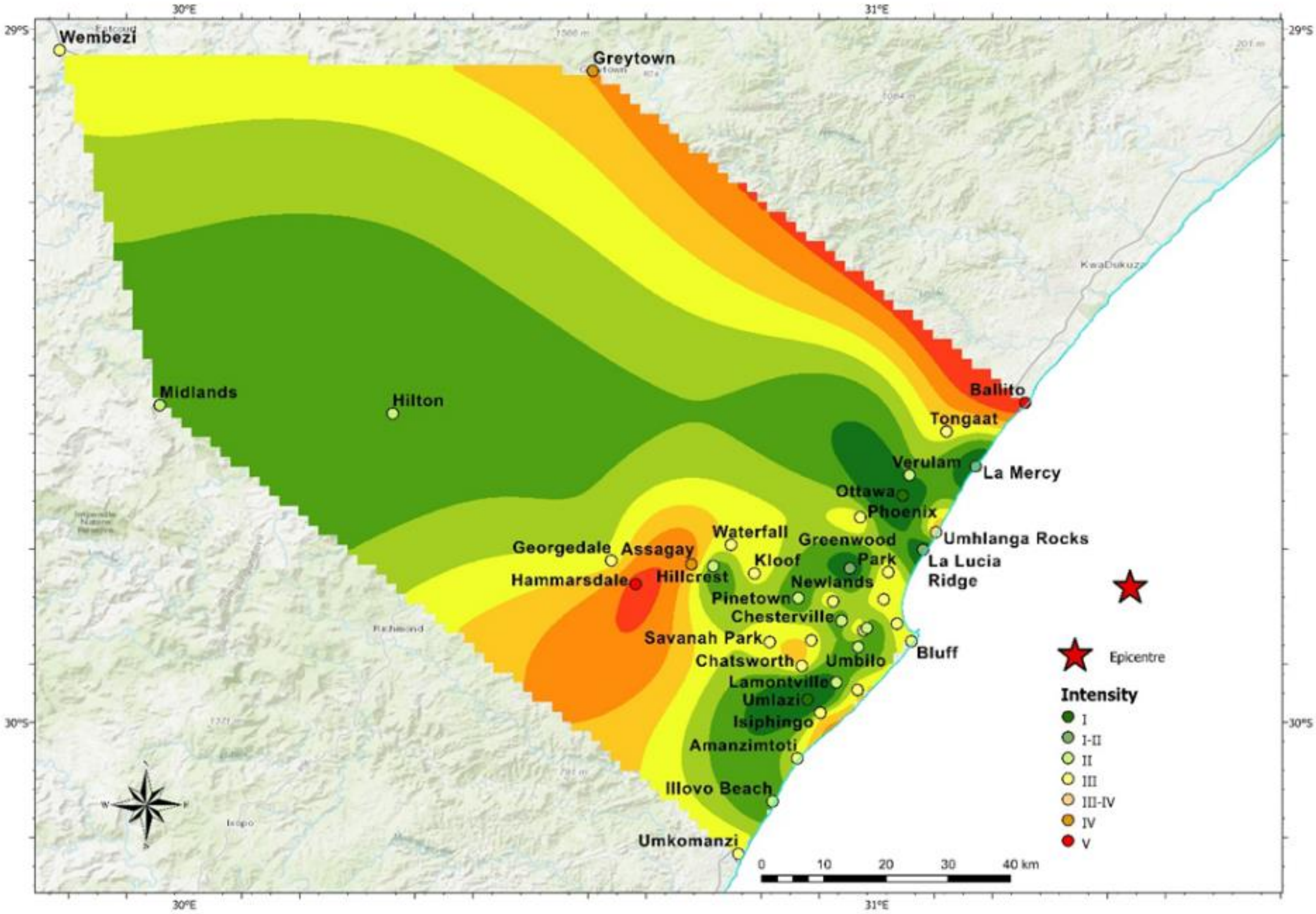


Figure 3.8 *Isoseismal map of the 6 February 2016, KwaZulu-Natal earthquake.*

3.7 Discussion and conclusion

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

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

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

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

Meunier et al. (2008), used earthquakes from California, Taiwan and Papua New Guinea suggested that steep areas are prone to topographic site effects. This could be the underlying cause of the high intensities that were experienced in some areas such as Greytown (1173 m), Assagay (827 m) and Hammarsdale (654 m) to the west in comparison to areas in the east, as seen in Figure 3.6. Assagay and Hillcrest are close to each other but there is a discrepancy in observed intensities between them. This scenario could have benefitted from the availability of more macroseismic observations in these areas to arrive at a more probable conclusion as there was a total of three observations altogether in these areas.

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

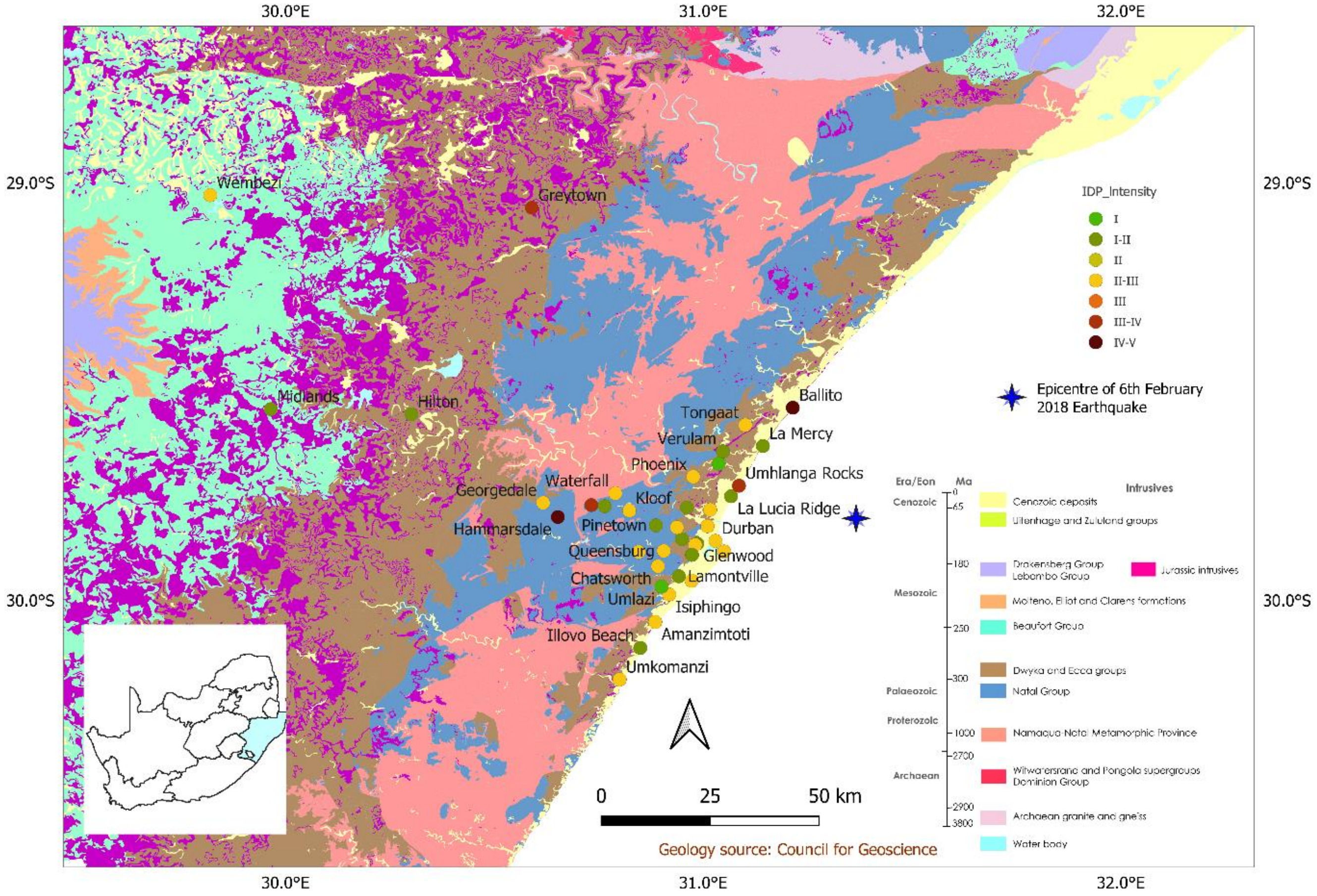


Figure 3.9 *Generalised geological units of the KwaZulu-Natal region, intensity data points of 6 February 2016 event plotted in the background (data from Council for Geoscience).*

The rocks of the province are of Archaean to Cenozoic age. A segment of the southern margin of the Archaean Kaapvaal Craton extends into northern KwaZulu-Natal (Figure 3.9). Together with the complex Namaqua-Natal Metamorphic province, they are the foundational geological units of the province. This margin of the Kaapvaal Craton is a granite-greenstone terrain (De Beer and Meyer, 1984). On the south-eastern flank of the Kaapvaal Craton in KwaZulu-Natal lies the Meso-Archaean Pongola Supergroup which is made up of the lower volcanic Nsuze and sedimentary Mozaan Groups (Wilson et al., 2013).

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

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

Seismic waves travel faster through the bedrock whereas the less consolidated colluvium would be prone to slowing down the seismic waves. This increases the amplitude and duration of ground shaking as the energy is entrapped, leading to more severe ground shaking than would be expected at a site (Liam-Finn and Wightman, 2003). Therefore, the anomalous intensity observed in these areas may be attributed to a combination of low-cost housing as well as amplification resulting from the acoustic impedance contrast of the colluvium and sandstone bedrock associated with shear wave velocity disparity. Similarly, the anomalous Ballito intensity data point may also be a result of amplification effects as it is located within the Cenozoic Maputaland Group, which consists of unconsolidated estuarine muds and shelly sands.

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

Chapter 4: Geophysical interpretation of the possible mechanism of seismicity in the Tugela Terrane with insights from the 16 June 2015 Sundumbili earthquake

4.1 Introduction

On the 16th of June 2015 at 05:21 hours local time (03:21 UTC), KwaZulu-Natal was struck by an earthquake of local magnitude M_L=3.1. The earthquake was recorded by International Monitoring System (IMS) stations shown in Figure 4.1. The epicentre of the earthquake was located near the coastal town of Sundumbili at -29.068° S and 31.462° E, at the boundary of the Kaapvaal Craton and Natal Metamorphic Province. The area is not densely populated, nor are there seismic monitoring stations nearby. The error ellipse of the location was found to be ±2.7 km and ±4.0 km in the major and minor axis, respectively. No aftershocks were identified after this event. According to Namole (2016), significant damage was caused near the Tugela River mouth, the local beach and a fishing spot, which is a source of livelihood for the local community (Figure 4.2). Like the 31 December 1932 earthquake which led to a tsunami, eyewitness stated that up to 100 m of beach area was inundated by water, indicating the vulnerability of KwaZulu-Natal to tsunamis.

This earthquake was not an isolated incident but is one amongst a string of seismic events that have been recorded in the area. This longstanding recurrence of earthquakes appears to be different from the earthquake swarms that occasionally happen in southern Africa such as the Augrabies swarm that petered out over time. The instrumentally recorded earthquakes in this area had a magnitude range of $1.0 \leq M_L \leq 4.3$ and occurred both on land and offshore. The seismic activity indicates that fundamental stresses are at work in the southern African crust that are released along specific zones of weakness at the suture of the southern margin of the Kaapvaal Craton and the northern edge of the Natal Metamorphic terrane. The fact that seismic activity in this area has been relatively pronounced suggests geological conditions that permit for small slippages along favourable structures exist in the area. This chapter attempts to associate these earthquakes with the geological lithology at the southern margin of the Kaapvaal Craton and Natal Metamorphic Province in KwaZulu-Natal, which has several faults that are either present due to the release of stress or are conveniently used to release stress. It is known that ultramafic rocks contribute to earthquakes by permitting easier slippage.

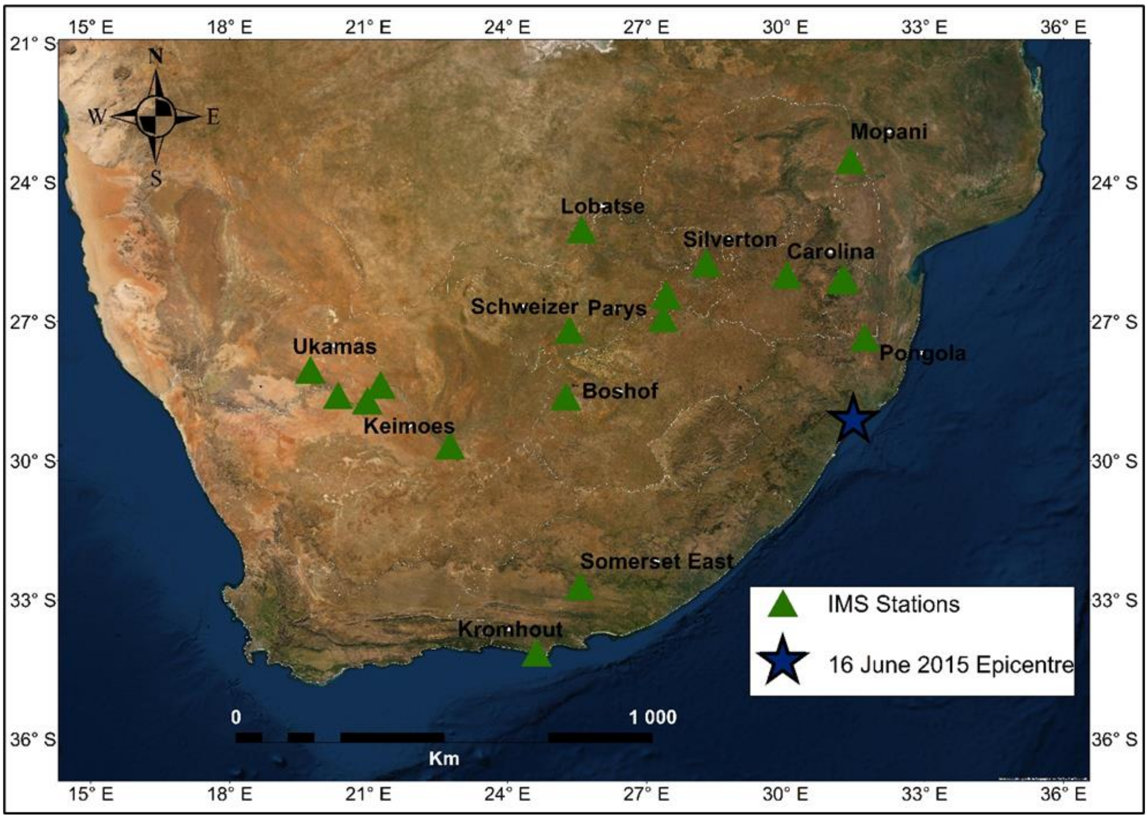


Figure 4.1 *The epicentre (blue star) of the 6 June 2015 earthquake and the International Monitoring Stations (IMS) used to analyse its location.*

Figure 4.2 *Damage caused by the disturbance in the tides after the Sundumbili 16 June 2015 earthquake (courtesy of Sanele Mkhwanazi).*

4.2 Epicentral location of the 16 June 2015 earthquake

The 16 June 2015 earthquake occurred at the thrust front that marks the contact between the Kaapvaal Craton and Natal Metamorphic Province (Figure 4.3). The Kaapvaal Craton forms the core of southern Africa and is one of the oldest pristine Archaean crusts in the world. It was formed and stabilised between 3.6 and 3.2 Ga with the oldest granodiorite rocks occurring south of the Barberton Greenstone Belt in South Africa and Swaziland (Poujol et al., 2003; McCarthy and Rubidge, 2005). It was formed in a multifaceted episodic manner that mimics modern-day plate tectonics. The process involved magmatic arc formation and accretion as well as tectonic amalgamation of numerous, discrete terranes or blocks (de Wit et al., 1992; Lowe, 1994; Poujol et al., 2003).

The Kaapvaal Craton gained in area and volume at ~2.7 Ga from the collision with the younger Zimbabwe craton. When the continental collision occurred, the sedimentary rocks on the floor of the contact ocean were subjected to compressive stress and the release of lava. This led to heat and pressure metamorphism during the 2.7 Ga orogenic event resulting in the formation of the Limpopo Metamorphic Province (Light, 1982; Wilson et al., 1995; McCarthy and Rubidge, 2005). Details of the suturing between the two cratons are not fully understood and palaeomagnetic studies also suggest that this event may have happened later (Barton and van Reenen, 1992).

The impact of this collision caused huge ruptures in the interior of the Kaapvaal Craton along both old and new fault lines. Due to possibly oblique pressure from the north, sections of the Kaapvaal Craton began to slide sideways to accommodate the pressure (Light, 1982; Kidd, 1984). Lava erupted along tensional release structures such as the faults along which Klipriviersberg Group. Lava poured through the rupture cracks about 2.7 Ga ago for a period of close to six million years and buried the Witwatersrand and older rocks below the Ventersdorp Super Group (Burke et al., 1985; McCarthy and Rubidge, 2005).

The Kaapvaal Craton then grew further during the Paleoproterozoic towards the end of the Ubendian event at 1.8 Ga with the accretion of crustal deposits on the western and southwestern perimeter of the Kaapvaal Craton (Vajner, 1974). At the southern and western margin of the Kaapvaal Craton lies the ~1400-km-long and 400 km wide Mesoproterozoic Namaqua-Natal Metamorphic Province. The eastern sector of the Namaqua-Natal Metamorphic Province, that is well exposed in KwaZulu-Natal, is known as the Natal Metamorphic Province. It consists of three discontinuity-bounded tectonostratigraphic terranes which are, from north to south, the Tugela, Mzumbe and Margate Terranes (Figure 4.3), with distinct lithology, structure and metamorphic grade (Jacobs and Thomas, 1994; McCourt et al., 2006; Cornell et al., 2006; Bisnath et al., 2008; Voordouw and Rajesh, 2012).

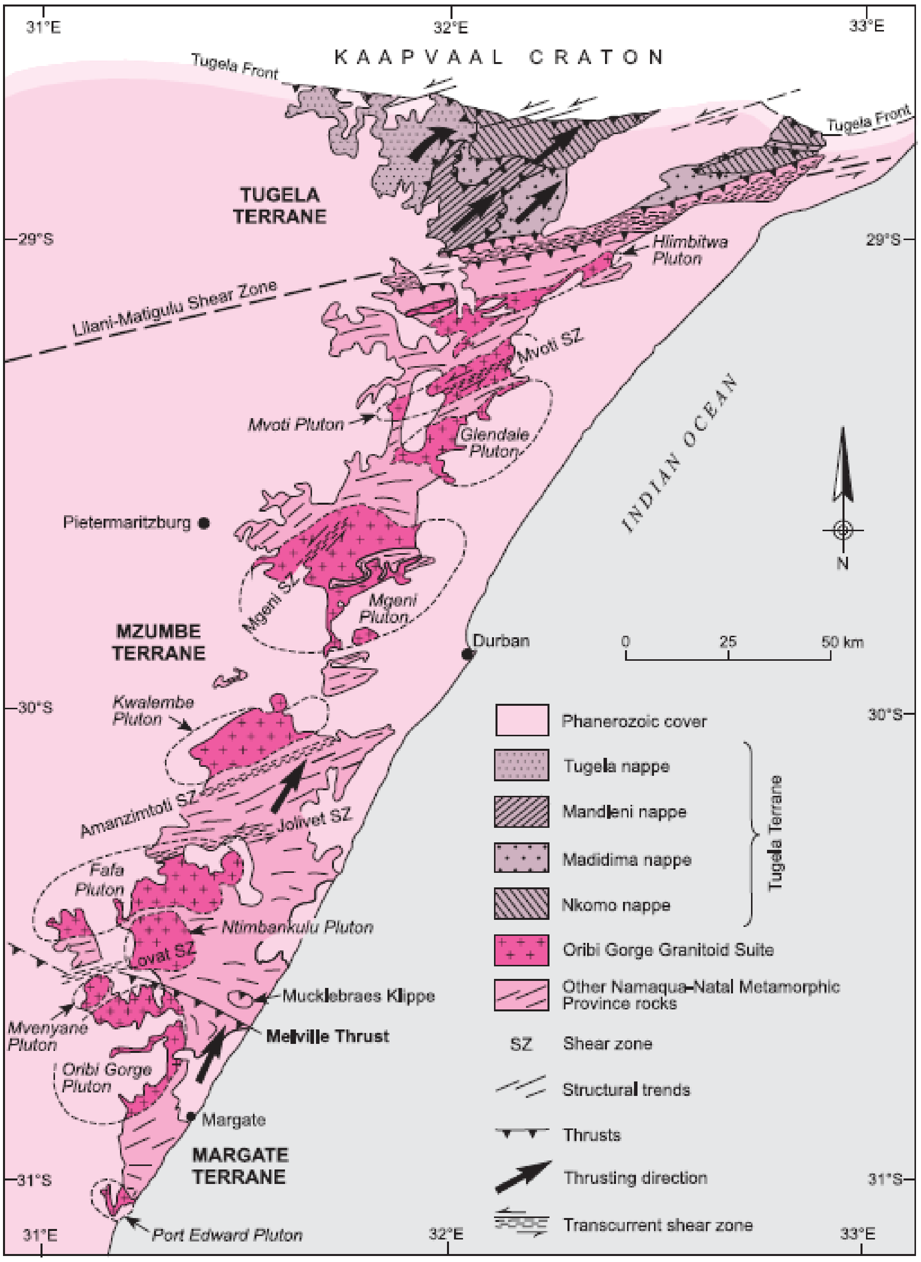


Figure 4.1 *Simplified geological map of the Natal Metamorphic Province showing tectonostratigraphic terranes, major thrusts, sinistral transcurrent shear zones and late tectonic granites (Cornell et al., 2006).*

Due to the presence of voluminous 1.2 to 1.0 Ga granitoid gneisses, the Mzumbe and Margate Terranes have been interpreted as deeply eroded magmatic arcs (Thomas, 1989; Thomas et al., 1992a; Thomas et al., 1999). It is postulated that the Mzumbe and Margate Terranes are magmatic arcs that developed in response to a Mesoproterozoic ocean basin closure south of the Kaapvaal Craton, with subduction away from the craton (Matthews, 1972; Matthews, 1981; Bisnath et al., 2008). According to (Matthews, 1990), the Lilani-Matigulu Shear Zone, which forms the boundary between the Tugela and Mzumbe Terranes, is a 3.0 Ga transform fault which separated the Kaapvaal Craton from the Tugela Ocean since the Late Archaean. The ultramafic remnants in the geology at the boundary of the southern margin of the Kaapvaal Craton and Natal Metamorphic Province have been interpreted as oceanic crust remnants caught up during the collisional event (Matthews, 1972). Jacobs and Thomas (1994) further stated that tectonic activity is still taking place at the Lilani-Matigulu Shear Zone as it was the site of a minor volcanic eruption in 1983 and several sulphur hot springs are located around this brittle fault, which was reactivated in post-Karoo times.

South Africa is an intraplate seismic region that is characterised by low to moderate levels of seismicity (Johnston et al., 1994; Brandt, 2011; Singh, 2016). Regional seismicity is largely dominated by anthropogenic events from mining gold, platinum and coal mines (Brandt et al., 2005; Saunders, 2017). However the strongest instrumentally recorded earthquake to occur in South Africa was the destructive 29 September 1969 M_L 6.3 Ceres-Tulbagh, which was far removed from any anthropogenic causes (Green and Bloch, 1971). In KwaZulu-Natal, the strongest earthquake was the 31 December 1932 St Lucia M_L 6.3 event which originated from a fault running parallel to the coast (Krige and Venter, 1933).

The Ceres earthquake occurred in the Cape Fold Belt, which is associated the Ceres, Kango, Baviaanskloof, Coega (C-K-B-C) fault system. The paleoseismic evidence suggests that part of the Kango fault is undergoing reactivation (Goedhart and Booth, 2016). However, the Tugela Terrane and southern Kaapvaal Craton boundary has consistently experienced seismic activity since earthquake monitoring started in South Africa. In this study we aimed to investigate the possible causes of this seismic activity from a geological perspective.

4.3 Review of seismicity patterns and tectonic structures of the Tugela Terrane and surrounds

4.3.1 Seismicity at the boundary of the Kaapvaal Craton and Natal Metamorphic Province

This area is characterised by moderate diffuse seismicity. The prominent E-W trending Tugela fault is considered an active fault as several hot springs (blue circles in Figure 4.4) are located along it and seismic events can also be associated with it (Singh, 2016). The occurrence of hot springs suggests the existence of pre-existing zones of weakness which are susceptible to reactivation and have also been found to have high geothermal gradients (Dhansay et al., 2017). Sobh et al. (2021), estimated a heat flow of ~80 mW/m^2 for this region. The largest earthquake in this area was the M_L 4.3 earthquake that occurred on the 3rd of February 1948 (green star in Figure 4.4). The seismicity map is shown in Figure 4.4. The spatial distribution of the events appears to be in a NE-SW trending pattern parallel to the coast. This appears to align with the coastal faulting of KwaZulu-Natal where pre-existing zones of weakness may have undergone reactivation due to NW-SE compression (von Veh and Andersen, 1990; Gold, 1993; Basson, 2000). The pre-existing zones of weakness may be due to favourable lithology along the boundary of the southern margin of the Kaapvaal craton and the Natal Metamorphic Province in KwaZulu-Natal where there are ultramafic rocks or remnants of

Gondwana breakup. It is interesting that the locations of these earthquakes are not far from the M_L=6.3 31 December 1932 earthquake, which leaves one wondering whether they could be related.

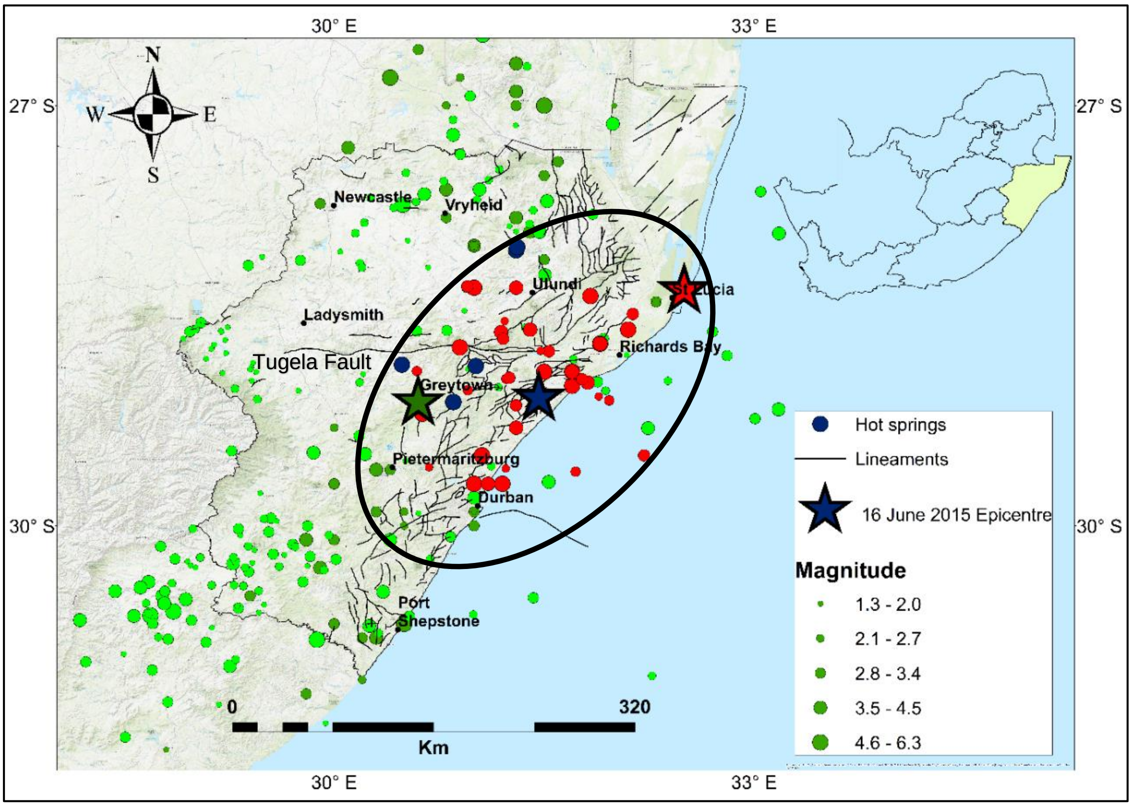


Figure 4.2 *Spatial distribution of seismicity along the Tugela Terrane with red star showing the location of the M_L=6.3 31 December 1932 earthquake and green star shows the M_L=4.3 the 3 February 1948 event. The red circles are historical events that occurred pre-1970.*

4.3.2 Regional geological settings

The formation of what is now known as the Namaqua-Natal Metamorphic Province has its origins in the formation of the Rodinia supercontinent. At about ~1.1 Ga most the Earth's crust was a single continent known as Rodinia. It was formed by the collision of the Nena with Ur and Atlantica subcontinents (Hoffman, 1991; Lutgens and Tarbuck, 2017). The collision zones where Rodinia was assembled when the subcontinents collided are marked by Grenville metamorphic belts. According to McCarthy and Rubidge (2005), these metamorphic belts consist of granite intrusions and folded sedimentary rocks that were metamorphosed during the subduction process, together with slivers of oceanic crust and island arcs.

Rodinia fragmented at ~700 Ma along the sutures when Laurentia broke away from Rodinia, with localised rifts also developing within the fragments during the breakout (McCarthy and Rubidge, 2005). According to Hoffman (1991), southern Africa was the pole of rotation about which the fragmentation took place. This arcuate Grenville belt that lies on the southern and western margins of the Kaapvaal Craton is now what is known as the Namaqua-Natal Metamorphic Province in southern Africa (Jacobs and Thomas, 1994; Cornell et al., 2006). Here we shall restrict ourselves to the Natal Metamorphic Province in KwaZulu-Natal, which unlike the more complex Namaqua sector is made up of entirely juvenile crust (Eglington et al., 1989).

According to Matthews (1972), the Tugela Terrane ophiolite complex of the Natal Metamorphic Province obducted onto the Kaapvaal Craton by northeast-directed thrusting and nappe emplacement between 1155 and 1140 Ma, followed by accretion of the Mzumbe-Margate Terranes between ~1091 and ~1070 Ma (McCourt et al., 2006). The southern margin of the Natal Metamorphic Province is obscured by Phanerozoic Karoo Supergroup cover rocks although geophysical modelling and deep Soekor boreholes showed that it is part of the larger Namaqua sector (De Beer and Meyer, 1984)

4.3.3 Local geological setting along the Tugela Terrane, Kaapvaal Craton boundary

The Natal Metamorphic Province is said to have undergone a complete Wilson Cycle and is comprised of supracrustal gneisses, granitoid gneisses and younger intrusive rocks (Matthews, 1972; Matthews, 1981).The Tugela Terrane records protracted magmatism in an island arc complex from ~1200 Ma to 1160 Ma (Spencer et al., 2015). It consists of ophiolite and amphibolite metavolcanic rocks which erupted at ~1.2 Ga together with mafic and felsic orthogneisses, layered mafic and ultramafic complexes and metasedimentary rocks (Matthews, 1972; Thomas et al., 1994; McCourt et al., 2006)

Matthews (1981) divided the Tugela Terrane into the narrow southerly dipping Natal Thrust belt in the north, adjacent to the Kaapvaal Craton, and the Natal Nappe Complex which is to the south. The Natal Thrust belt is known as the Ntingwe Group which predominantly consists of limestone conglomerates and shales unconformably overlying the south dipping cratonic foreland (Matthews, 1981; Basson and Watkeys, 2003). The Ntingwe Group is overlain to the south by the highly deformed Mfongosi Group, forming the upper part of the ophiolite complex. The Mfongosi Group is a sequence of greenschist facies metabasic lavas (epidote amphibolite and chlorite schist) and interlayered quartz-sericite schists (Jacobs and Thomas, 1994; Basson and Watkeys, 2003).

The Natal Nappe Complex towards the south consists of four flat-lying to moderately southerly inclined thrust sheets with a distinct tectono-magmatic signature (Jacobs and Thomas, 1994; Arima et al., 2001). Figure 4.3 shows the thrust sheets known as, from east to west, Nkomo, Madidima, Mandleni, and Tugela thrust sheets (Matthews and Charlesworth, 1981; Cornell et al., 2006). The thrust sheets are mainly composed of granitic gneiss, para-amphibolite, meta-basalt, magnetite quartzite and ultramafic pods and lenses (Matthews, 1981). The nappes were intruded by, and are tectonically interleaved with layered mafic and serpentinised ultramafic plutonic rocks, the latter with podiform chromite, pyroxenites and peridotites (Basson, 2000). According to Matthews (1972) the

Tugela nappes represent the lower oceanic crust section of the ophiolite complex (ocean floor basalts and pelagic sediments).

The Mzumbe and Margate Terranes are juxtaposed at the ~1 km wide south-west dipping Melville Thrust which is characterised by a high strain and where the Margate Terrane structurally overlies the Mzumbe Terrane (Thomas, 1989). They consist of arc-related, felsic to mafic metavolcanic and metasedimentary gneisses, the oldest of which (Quha gneiss) have been dated at ca. 1235 Ma (Thomas et al., 1999). The Mzumbe Terrane is dominated by amphibolite facies whereas the Margate Terrane displays very high temperature granulite metamorphism (Thomas, 1989; Jacobs and Thomas, 1994).

U–Pb zircon constraints by Eglington et al. (2003) suggest that the Mzumbe and Margate Terranes were intruded by the voluminous suite of rapakivi granite-charnockite plutons known as the Oribi Gorge Suite at ∼1070 and 1030 Ma. The intrusion took place after they had been juxtaposed during a tectonic phase known as the D_1 (Jacobs and Thomas, 1994; Jacobs et al., 1997). According to U–Pb data from zircon, titanite, and monazite constrains the temporal framework of these geological events, and the Tugela and Mzumbe Terranes record shows a protracted magmatism in an island arc complex from ∼1200 Ma to 1160 Ma, followed by the accretion of these terranes onto the southern margin of the Kaapvaal Craton at ∼1150 Ma. Arc magmatism in the Margate Terrane continued until ∼1120 Ma and was followed by extension and bimodal volcanism immediately prior to accretion to the Kaapvaal/Mzumbe continental margin at ∼1090 Ma. This accretion was accompanied by high-pressure and high-temperature metamorphism, juxtaposition of the Mzumbe and Margate Terranes along the Melville Thrust, and the formation of several syntectonic intrusive units derived from melting of the pre-existing arc crust. After accretion, extensional collapse is evidenced by the intrusion of mafic/ultramafic and alkaline intermediate magmatic suites at ∼1085 Ma, resulting from mafic underplating and/or lower crustal delamination.

4.3.4 African plate geodynamics in southern Africa

The East African Rift System is a seismically and volcanically active divergent plate boundary that separates the Nubian and Somalian plates and is the largest continental rift in the world (Rajaonarison et al., 2021). The Nubian plate (Figure 4.5) is located on the west while the Somalian plate is located on the east of the East African Rift System. According to Stamps et al. (2018), the strain at the African Rift System is accommodated at the boundaries of the Rovuma, Lwandle and Victoria microplates. The strain at the East African Rift System is generally extensional except to the southeast of southern Africa, south of the proposed triple junction of the Rovuma, Lwandle, and Nubian plates, where it is compressional (Stamps et al., 2014). The seismic activity and geomorphic structures in southern Africa have for many years led to suggestions that active tectonics is taking place within the Nubian plate which is not rigid, and that it may be undergoing incipient rifting (Scholz et al., 1976; Fairhead and Henderson, 1977; Saria et al., 2013).

Thermomechanical modelling by Rajaonarison et al. (2021), suggested that lithospheric buoyancy forces drive ~E-W extension across East Africa Rift System that results from rigid block rotation with rates decreasing from 6–7 mm/year in the Main Ethiopian Rift, 3–4 mm/year in the central East Africa Rift System, to less than 1 mm/year south of Mozambique. The seismicity in the southeast of southern Africa as well as Okavango, Mweru, Luangwa rifts and the Cameroon volcanic line has been associated with active deformation and mainly occurs along the weak suture zones between the cratons and metamorphic belts (Reeves and De Wit, 2000; de Wit et al., 2008). Additionally, the east of South Africa experiences higher strain rates than the rest of the country (Malservisi et al., 2013; Stamps et al., 2018). Although various studies along the East African Rift System have resulted in slightly different strain rate magnitudes due to a lack of quality geodetic observations, it is notable that the models have comparable patterns (Saria et al., 2013; Stamps et al., 2008; Stamps et al., 2014; Stamps et al., 2015).

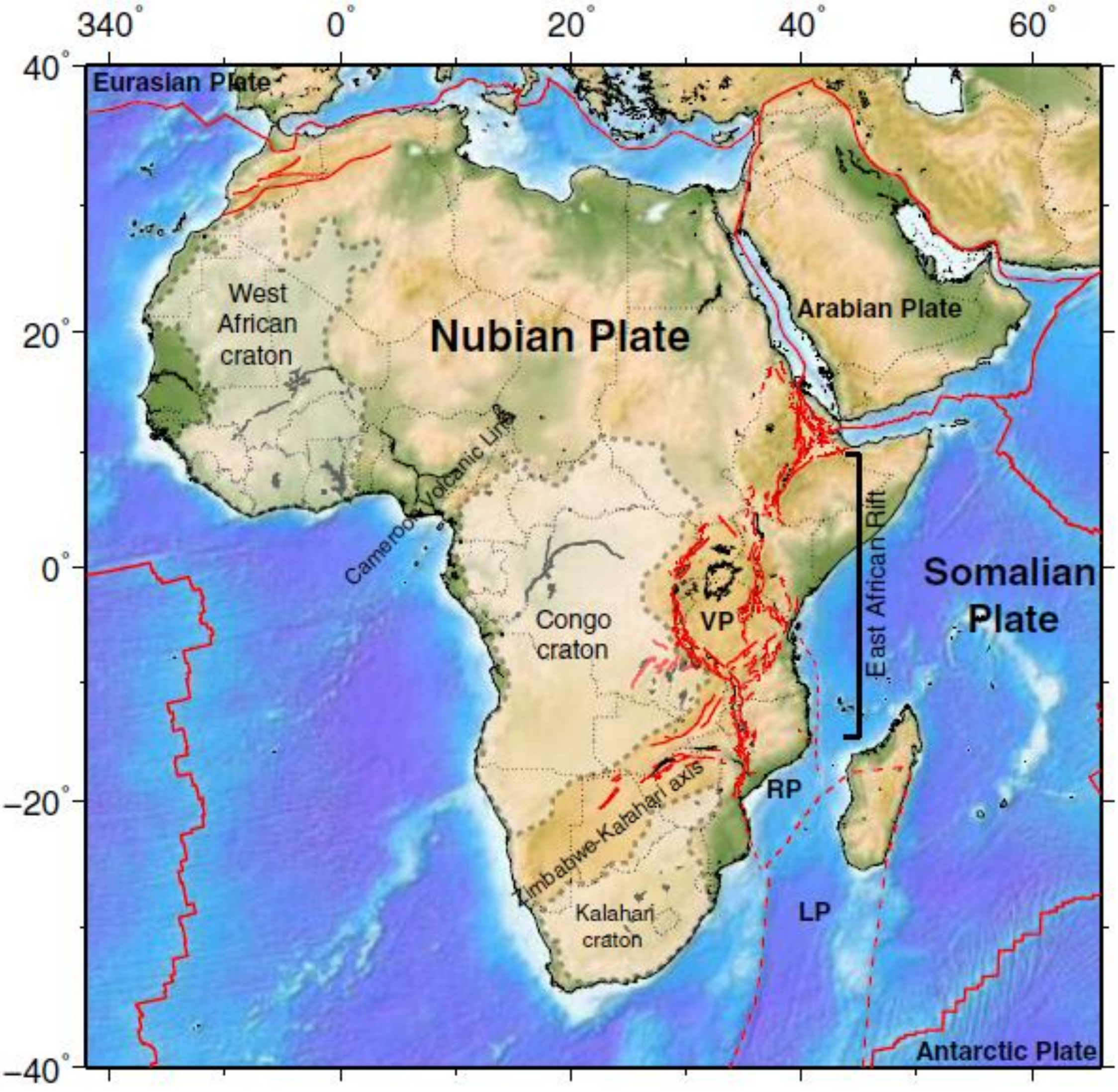


Figure 4.3 *Major tectonic features in Africa. Red lines show the major plate boundaries, solid where they are well defined, dashed where they are assumed. VP: Victoria Plate, RP: Rovuma Plate, LP: Lwandle Plate (Saria et al., 2013).*

Ridge-push forces due to lithospheric cooling and subsidence from the mid-ocean ridges also contribute to the movement of the Nubian-Somalian plate system movement plate (Stamps et al., 2010). According to Zoback et al. (1989) and Mahatsente and Coblentz (2015), north east oriented ridge-push forces from the Mid-Atlantic Ridge are transmitted to the Nubian plate which moves northeast and abuts against the Somalian plate. This means that present-day stress fields in the Nubia-Somalia plate system may be caused by lateral variations of lithospheric structure and thicknesses in the African continent, and gravitational potential energy forces associated with the surrounding mid-ocean ridges.

Bird et al. (2006), on the other hand, suggested that southern Africa is in a state of extension rather than compression originating from surrounding mid-ocean ridges because its high elevation leads to density moments that exceed those originating from mid-ocean ridges. Stamps et al. (2008) and Calais et al. (2006) estimated that this extension is directed approximately E-W all along the rift, with rates decreasing from 6-7 mm/year in the Main Ethiopian Rift, 3-4 mm/year in the central East African Rift System, to less than 1 mm/year south of Mozambique. The African Superplume, a broad topographic anomaly on the eastern and southern African plateaus, has also been associated with intraplate volcanism and rifting, as well as with seismic and other quantitative evidence of anomalous mantle features below the continent (Nyblade and Robinson, 1994; Bagley and Nyblade, 2013; Rajaonarison et al., 2021). Even though the contribution scale on continental geodynamics is enigmatic, there is a consensus that regional stresses within the continent originate from intra-continental rifts, mid-oceanic ridges, and large-scale topographic features.

4.4 Macroseismic survey of Sundumbili earthquake and geophysical modelling of the Tugela Terrane

4.4.1 Macroseismic survey of the 16 June 2015 Sundumbili earthquake

Following the occurrence of the 16 June 2015 earthquake, the University of KwaZulu-Natal conducted a macroseismic survey to investigate the effects of the event. The field teams surveyed areas along the coast from Ballito to KwaMbonambi in the north. The survey was primarily done using a questionnaire provided by the Council of Geoscience, comprised of 24 multiple choice intensity indicator questions which had been used for similar studies in South Africa such as by Midzi et al. (2015b) and Mapuranga et al. (2022). The questionnaires also requested the address of the participant to determine their spatial location at the time when the earthquake occurred. The initial data analysis was done by Namole (2016).

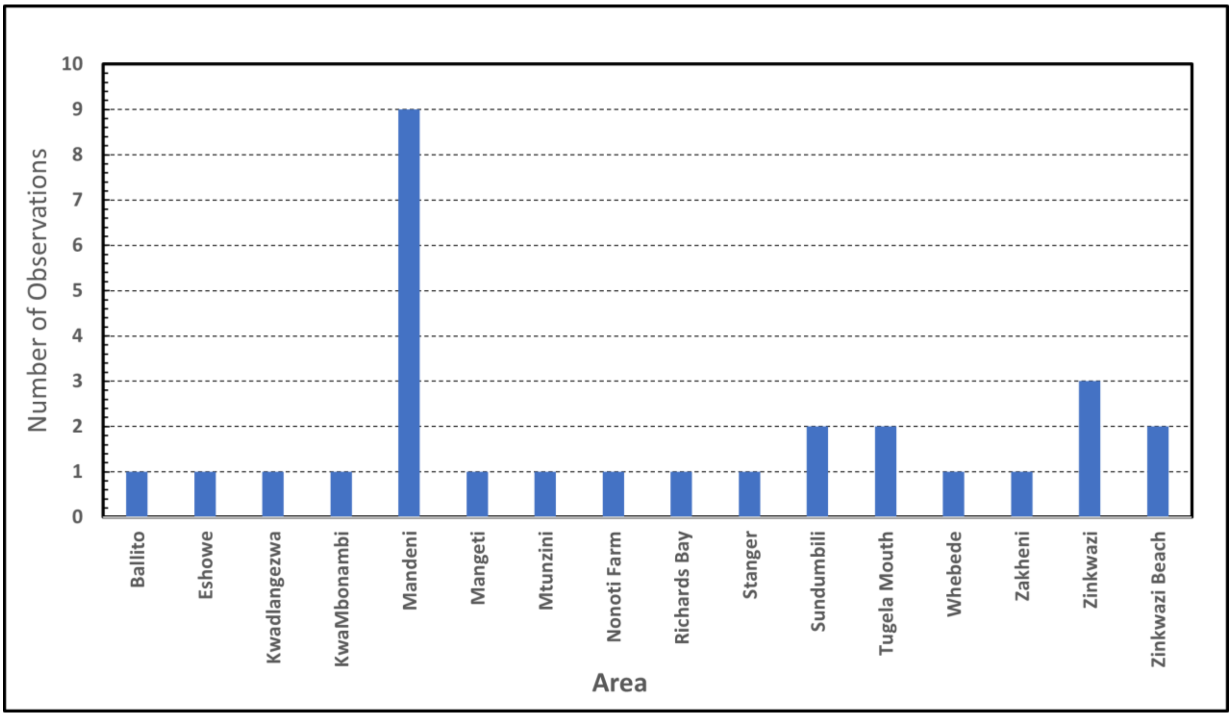


Figure 4.4 *Number of observations used to create intensity data points.*

Due to limited financial resources, only a total of twenty-nine observations (Figure 4.6) were collected and translated into intensity data points using the procedure of Musson and Cecić (2002). This method involves sorting the observations according to the suburb or district they were reported from and summarising the information from the questionnaire. Thereafter an intensity is estimated for each area based on the Modified Mercalli Scale of 1956 (MM56) of Richter (1958). The locations of the suburbs and districts were obtained from the National Geospatial-Intelligence Agency online database tool (http://geonames.nga.mil/namesgaz). The number of intensity data points obtained for each intensity level and their spatial distribution are shown in Figure 4.7 and 4.8 respectively.

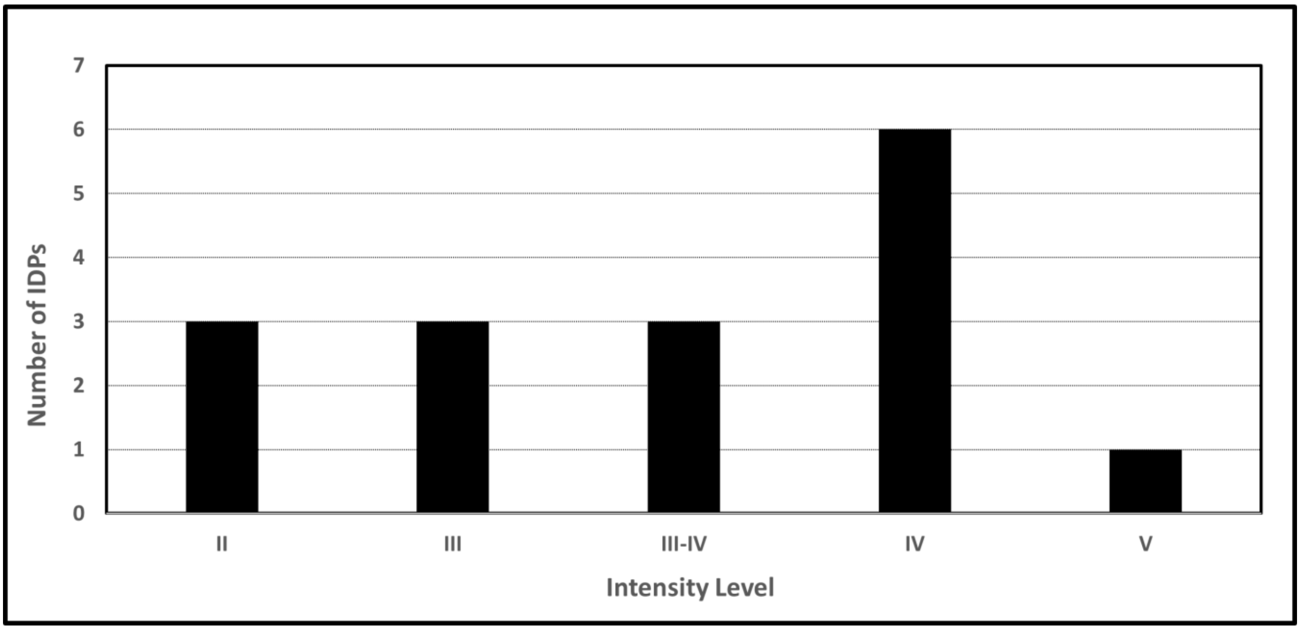


Figure 4.5 *The number of intensity data points obtained for each intensity level.*

The greatest number of intensity data points had an intensity level of IV while levels II, III, III had three intensity data points each. Only Mandeni had an intensity level of V. The isoseismal map from the intensity data shows a gradual decrease in intensity as one goes further from the epicentre. This is not surprising as the level of intensity experienced in a particular area depends on the strength of the earthquake, local geology conditions and distance from the epicentre. Although more online news outlets reported on the effects of this earthquake, these were not included because the locations of the sources at the time of the earthquake could not be ascertained from them, which is necessary for analysing macroseismic data. The reports included burst water pipes, damaged swimming pools and cracked walls in KwaMbonambi (Jolly, 2015).

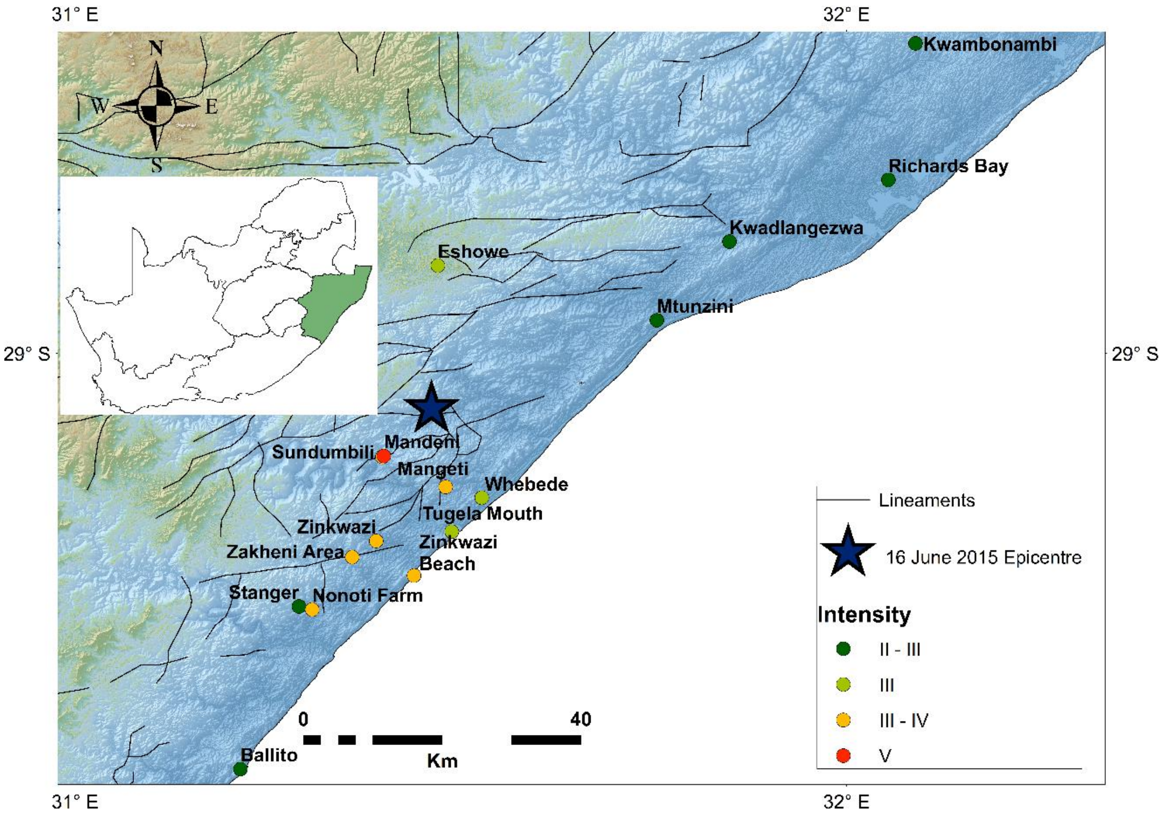


Figure 4.6 *Spatial distribution of intensity data points superimposed on the topography of KwaZulu-Natal and epicentre of 16 June 2015 earthquake (blue star).*

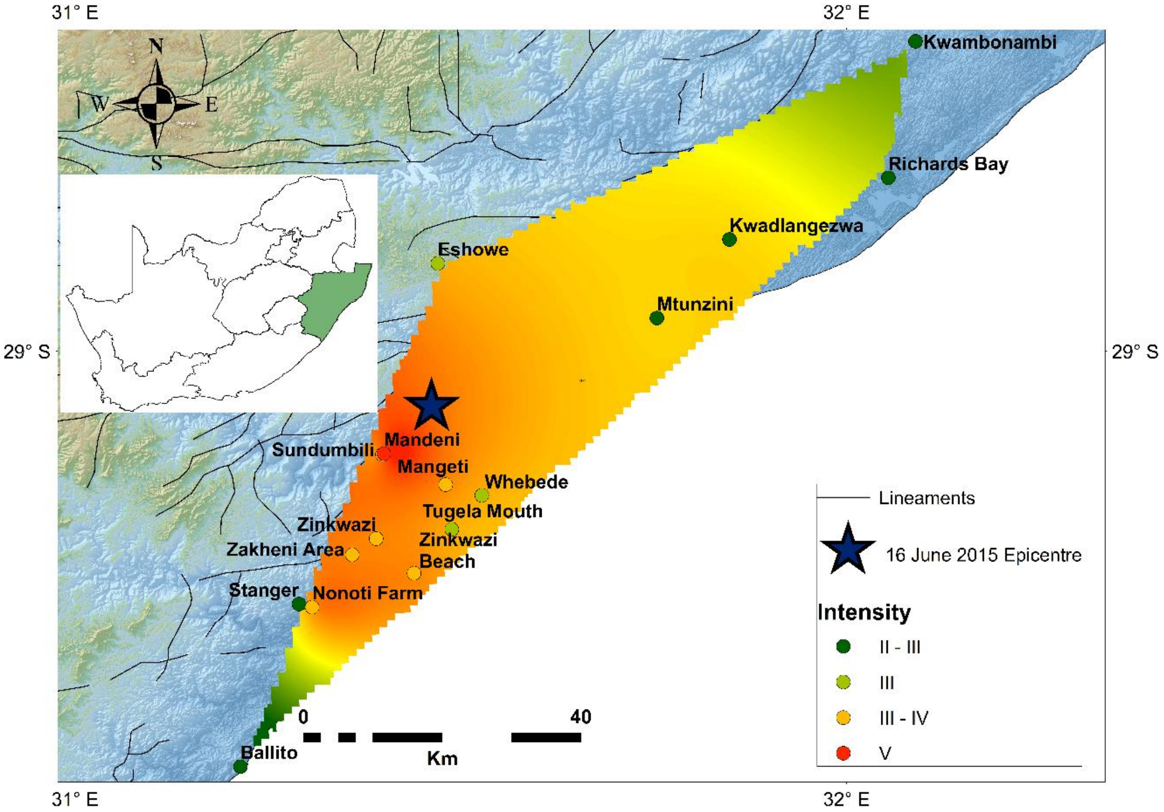


Figure 4.7 *Isoseismal map of the 16 June 2015 earthquake.*

4.4.2 Isostatic and Bouguer gravity

Gravity data have been collected in South Africa from 1939 by various institutions such as the Bernard Price Institute of Geophysical Research, Council for Scientific and Industrial Research, Geological Survey (now the Council for Geoscience), University of Cape Town, Department of Water Affairs and several other institutions (Stettler and Kleywegt, 2015). Gravity measurements undertaken before 1970 were standardised to the 1930 International Gravity Formula which was based on pendulum measurements taken in 1906 in Potsdam which are believed to be in error by about 14 mGal (Smit, 1962). As the definition of the geoid improved, a new standard was adopted, the so-called IGSN71 (Morelli et al., 1972) and all the gravity measurements used here were corrected to the IGSN71 reference. The density used for the Bouguer correction was 2670 kg/m^3, the average density of the surface rocks of the continents (Hinze, 2003).

All regional Bouguer anomaly data available at the Council for Geoscience were terrain-corrected in 2004 using an algorithm based on the formulation of the gravity effect of a parallelepiped (Stettler, 1979). The terrain corrected Bouguer gravity is shown in Figure 4.10. Subsequently the terrain corrected Bouguer anomaly values were isostatically corrected with the Airy-Heiskanen approach using an assumed, from sea-level, crustal thickness of 30 km as reference (Figures 4.11). The Airy-Heiskanen approach assumes crustal and mantle densities are laterally constant and the variation in surface relief is compensated by the change in the thickness of the crust or depth to the Moho discontinuity (Hinze et al., 2013). According to this model, mountains have “roots” and valleys/seas “anti-roots” of crust with similar density, supporting them in hydrostatic equilibrium. This means that the surface topography has a mirror image underneath, exaggerated by a factor of 4.45 (assuming a crustal density of 2670 kg/m^3 and sub-crustal density of 3270 kg/m^3) every topographic feature is compensated by a root or anti-root, regardless of how small it may be (Lowrie, 2007). The isostatic correction was calculated using a variation of the Stettler (1979) algorithm.

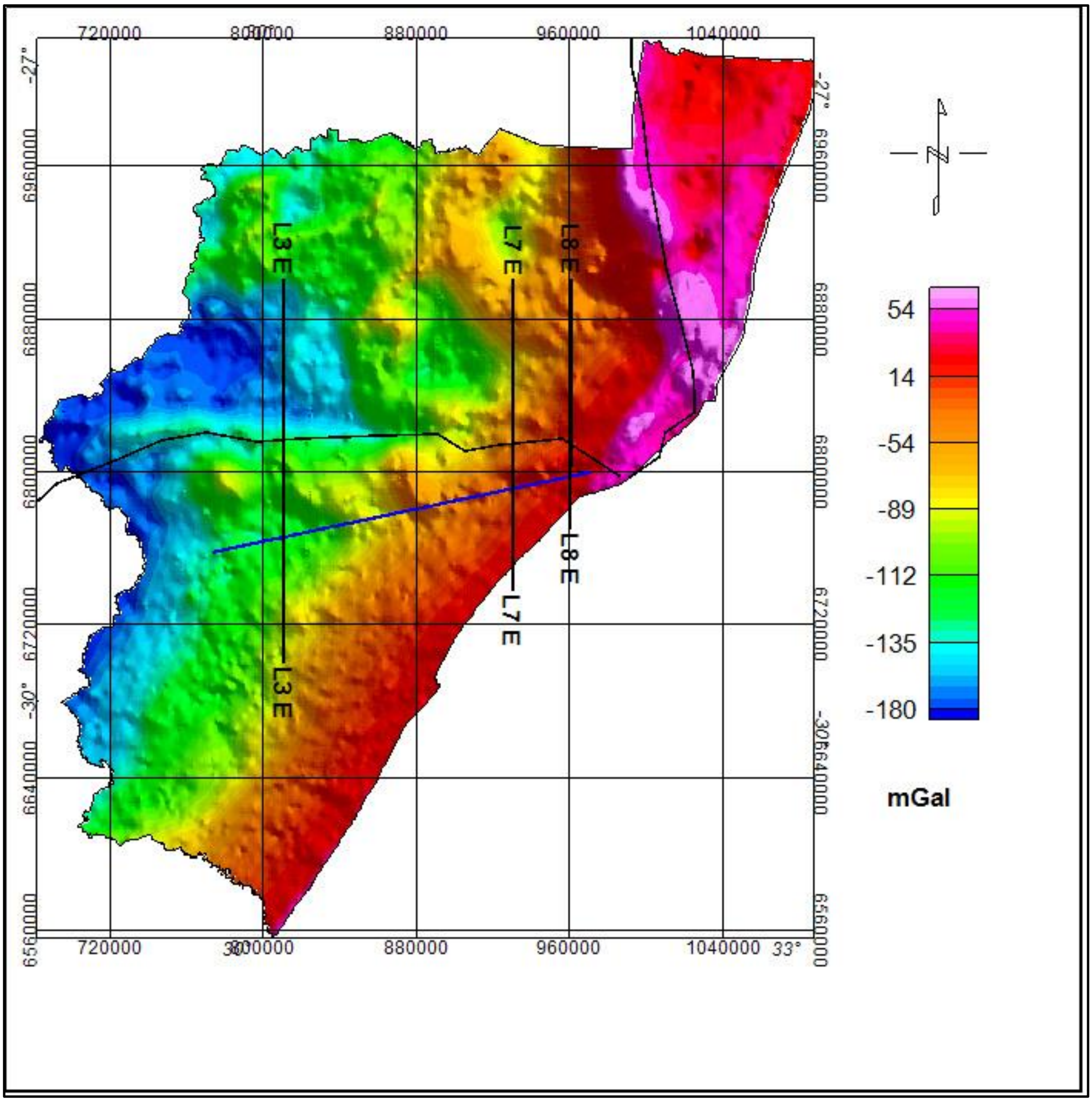


Figure 4.8 *Terrain corrected Bouguer gravity anomaly map of KwaZulu-Natal with Kaapvaal Craton outline and Lilani-Matigulu Shear Zone in black and blue respectively.*

The terrain corrected Bouguer gravity anomaly shows a gradually increasing trend from the west towards the coast in the east due to the influence of the oceanic basalts and ranges from -180 to 80 mGal in the province. The largest Bouguer gravity anomaly values are observed along the volcanic Lebombo belt, on the eastern Kaapvaal Craton margin which is a remnant of the Gondwana breakup where it is highest near latitude 26ºS and where rhyolites overlap the lower Karoo basalts (Darracott and Kleywegt, 1974).

An interesting feature that can be seen in the terrain corrected Bouguer gravity anomaly data is the distinct linear anomaly that is observed with an EW trend at approximately 26ºS. This anomaly possibly marks the transition zone between the southern margin of the Kaapvaal Craton and the northern edge of the Natal Metamorphic Province.

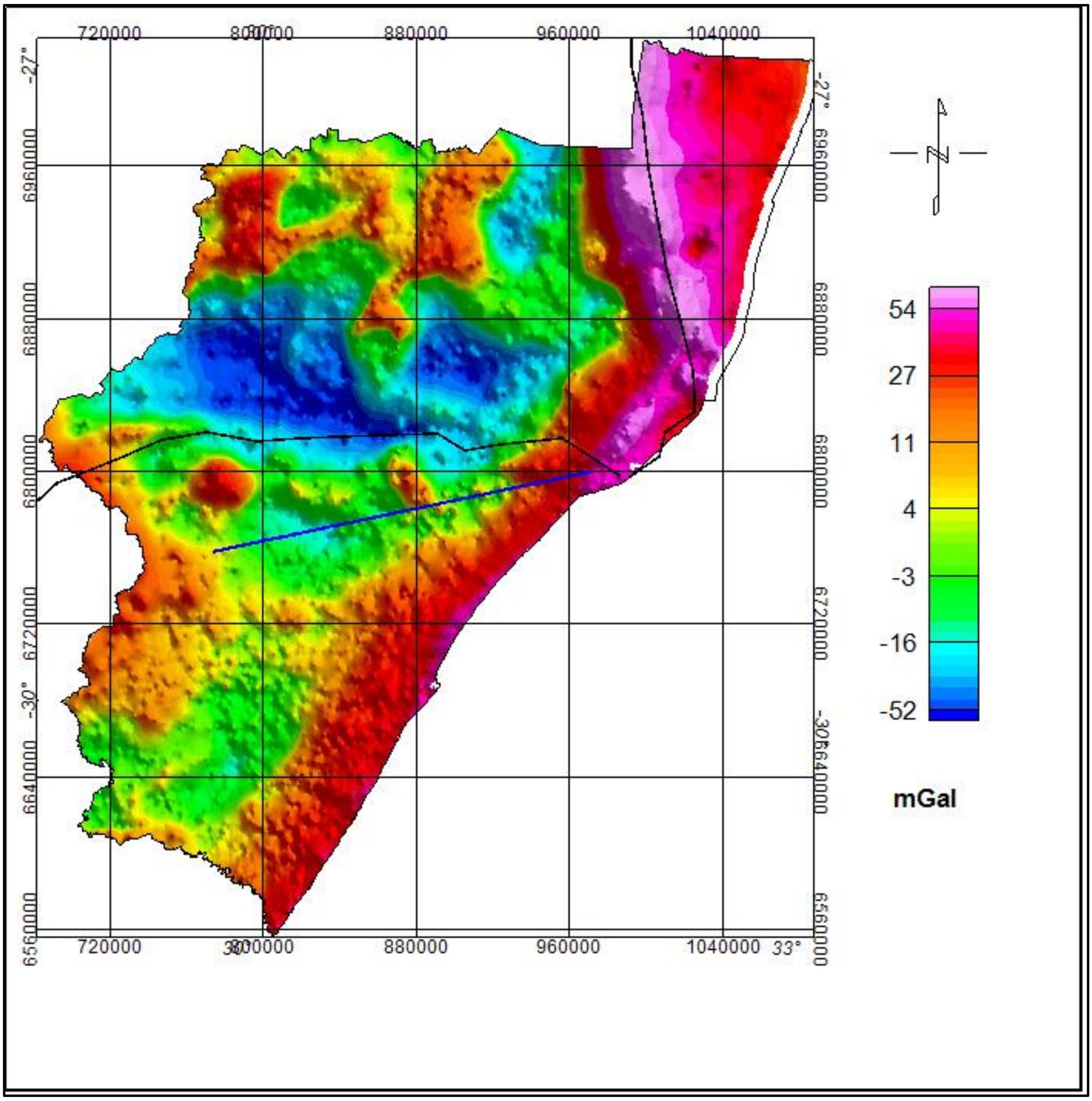


Figure 4.9 *Airy-Heiskanen isostatic anomaly map of KwaZulu-Natal with Kaapvaal Craton outline and Lilani-Matigulu Shear Zone in black and blue respectively.*

The isostatically corrected gravity data ranges from approximately -52 to 95 mGal. The values are mostly slightly negative on the continent and increase going eastwards towards the coast becoming increasingly positive in the proximity of the coast. On the continental crust, barring the presence of a geological entity in the crust with a density different from the 2670 kg/m^3 a negative isostatically corrected gravity value signifies crust pressing into the mantle, having a deeper 'root' below sea level than the corresponding calculated surface elevation above sea level would allow and vice versa. The gradual increase in isostatically corrected gravity towards the coast again signifies the proximity of the higher density oceanic crust.

Over the Lebombo range the isostatically corrected gravity data increases gradually from south to north as well as along the Mozambique coast because of the denser Lebombo volcanics in the north (Figure 11). An anomaly high is also observed west of KwaZulu-Natal, at the border with Lesotho where the altitude is > 1200 m and possibly underlain by denser Karoo lavas in the crust or less likely, a mantle dome protruding into the crust. In central KwaZulu-Natal, striking sympathetically with the Tugela Front, there is a sharp negative anomaly trend which gives an indication of the state of isostatic compensation in the area and indicates an uncompensated by topography, thickening of the crust i.e., a crustal root is pushing into the crust.

4.4.3 Aeromagnetic data

Aeromagnetic surveys were flown in South Africa between 1958 and 1995 (Stettler and Kleywegt, 2015). The first assembly of all the data was undertaken in 1999 (Stettler et al., 2000). The coverage shown in Figure 4.12 covers the Margate survey, Block 16-73 and the Karoo 15, 16 and 17 blocks (Ledwaba et al., 2009) and stems from Stettler et al., (2000). Figure 4.12 shows an enhanced image where an upward continued by 1 km, regional field was removed to highlight the finer details in the residual (i.e., total field minus regional) data. The surveys were undertaken at 1 km line spacing and flight height was between 100 and 150 m (Ledwaba et al., 2009). The residual data displays a diverse magnetic signature which shows where the KwaZulu-Natal crust has magnetic anomalies that can be associated with the known geology of the province with a high magnetic susceptibility (high magnetite content).

The high amplitude NE-SW trending feature, (blue line in Figure 4.12) corresponds to the Lilani-Matigulu Shear Zone. The sub-parallel linear anomalies south of the Lilani-Matigulu Shear Zone, correspond to the other known shear zones in the area which include the Mvoti, Mgeni and Amanzimtoti Shear Zones. The nearly circular plug-like features that can be seen (highlighted by arrows) between the linear anomaly associated with the shear zones are likely the Oribi Gorge plutons (see Figure 4.3) which are linked to magmatism of the mafic and felsic intrusions (Jacobs et al., 1993). The localised strong and short wavelength magnetic anomalies that are seen just south of the Kaapvaal Craton (black line in Figure 4.12) are probably from ultramafic intrusions and in part are from increased magnetisation that arises from the process of hydrothermal alteration that transforms minerals such as olivine, pyroxene, or amphiboles contained in ultramafic rocks, into serpentine minerals (Marshak, 2013). The faulted Lebombo belt in the northeast corner of KwaZulu-Natal is again well delineated in the magnetic data. It features thin linear north-south trending magnetic anomalies which are probably interconnected at depth to mafic dyke swarms that intruded during the Gondwana break-up.

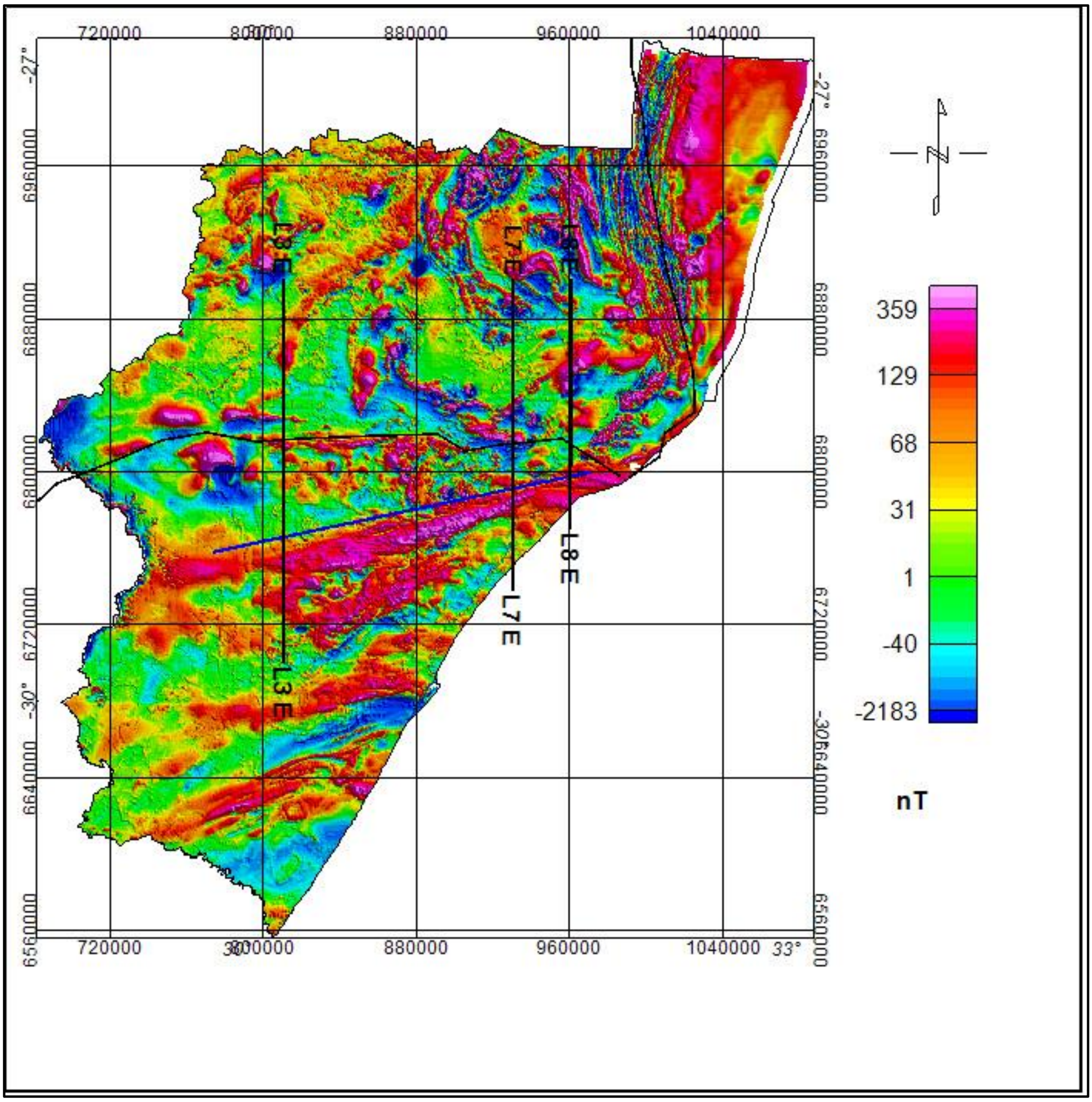


Figure 4.10 *Upward continued magnetic map of KwaZulu-Natal with Kaapvaal Craton outline and Lilani-Matigulu Shear Zone in black and blue respectively.*

4.4.4 Gravity and magnetic models

To validate the model of Matthews (1972), that the ophiolitic Tugela Terrane was obducted onto the south dipping Kaapvaal Craton and emplaced itself between the accreting Natal Metamorphic Province and Archaean craton, geology models of the subsurface were digitally built to compare the model's gravity and magnetic response to observed measurements. Seafloor basalts are dense with an average density of 2860 kg/m^3 before being emplaced by convergent plate boundaries and converted into ophiolites (Carlson and Herrick, 1990). These ophiolites, in addition to deep-sea sedimentary rocks and minerals, contain mafic and ultramafic minerals with an abundance of serpentine which is a product of hydrated olivine. Serpentine is a soft rock (hardness between 2 and 3 on the Mohr scale) with large density variations between 2400 and 3100 kg/m^3 and an average density of 2780 kg/m^3 (Telford et al., 1990). It would be hard to predict the average density of the ophiolite, but the crux would be to determine if the mapped ophiolite has a recognisable gravity and magnetic signature that would reasonably demonstrate that enough material underlies the mapped ophiolites to support the ophiolites to extend to a depth of at least between 5 and 10 km, i.e., the shallow earthquake depth.

It is well known that the process of hydrothermal metamorphism occurs when oceanic plates move apart (Marshak, 2013; Lutgens and Tarbuck, 2017). The upwelling magma from the mantle generates new seafloor. Seawater percolating through the young, hot oceanic crust is heated and hydrates the magnesium and iron-rich minerals like olivine and pyroxene from the magma, to form magnesium-rich serpentine minerals which are highly magnetic and are constituents of ophiolites (Lutgens and Tarbuck, 2017). These minerals also allow lubrication of suture zones and permit steady creep along zones of weakness such as the faults and the ophiolite lithology at the boundary of the southern margin of Kaapvaal Craton and Natal Metamorphic Province in KwaZulu-Natal.

Prior to postulating models to determine if the stress release mechanism can be explained by slippage along the Tugela-Kaapvaal front a few constraints have to be set, to allow for realistic models. In the northern part of the Kaapvaal Craton the depth to the Moho as determined from *Pn* arrival times is 50.52 ±0.88 km that reduces to 38.07±0.85 km in the south of the craton. Estimates from receiver functions are 43.58±0.57 and 37.58±0.7 km (Nguuri et al., 2001; James et al., 2003).

De Beer and Meyer (1984) used a mantle density of 3240 kg/m^3 and an average of 2810 kg/m^3 for the Kaapvaal Craton-Natal Metamorphic Province transition zone and obtained a crustal thickness of about 26 km in the transition zone. Estimates of the density of the felsic material just above the Moho is determined from seismic data as 2860 kg/m^3. There is also a 15% density difference across the Moho which would result in a density of approximately 3290 kg/m^3 for the material below the Moho (James et al., 2003). These values allow the following approximate density contrast constraints to be placed on the crust in the KwaZulu-Natal sector of Kaapvaal craton, with respect to the density of the upper mantle below the Moho:

Table 4.1: Approximate density constraint values

	Density range (kg/m^3)	**Density (kg/m^3)**
Upper crust	2650-3290	-640
Middle crust	2800-3290	-490
Lower crust	2800-3290	-410

Another constraint to be placed is that of the Curie Temperature where rocks lose their magnetic properties. The Curie Temperature for magnetic minerals is about 580 ºC that would translate on the Kaapvaal craton to a depth of approximately 46 km (Sobh et al., 2021).

Geology, elevation, isostatically corrected gravity (AH30), terrain corrected Bouguer anomaly (BA), and total field magnetic data were taken from three traverses with a south to north direction (black vertical lines in Figure 4.13). The original data are from the Council for Geoscience regional geological and geophysical published data sets. The lines are 100 km long and the data sampled at a 100 m sampling distance along the lines. In total, eight profiles were extracted that all affirmed the validity of the basic model postulate as proposed by Matthews (1972) but only three profiles are depicted here. The data along the traverse are displayed in Figures 12, 13 and 14 as well as a 2.5D model of the likely geological scenario as postulated from Mathews (1972) and built on by Thomas et al., (1994) and McCourt et al., (2006).

For the total field magnetic data, the strength of the earth's magnetic vector and orientation of the inducing field were taken as 28 000 nT, with a declination of -18º and inclination of -67º.The modelling was carried out using the proprietary GM-SYS algorithm (Seequent, 2021) which calculates the response of potential field data based on the approach of Talwani and Heirtzler (1964). The algorithm permits the interactive modelling of causative 2.5D bodies with given physical properties of magnetic susceptibility and density. An appropriate regional field was removed to isolate anomalies of interest from the longer wavelength features. The purpose of these models is to indicate whether a south dipping Kaapvaal Craton with obducted ophiolite in the suture zone between the southern margin of the Kaapvaal Craton and Natal Metamorphic Province in KwaZulu-Natal is feasible. The models were constrained by the broadly known geology together with the potential field data both supporting the same basic postulated model and the constraints of densities and Moho depth as obtained from earthquake seismic data.

Traverse 3 has mostly Karoo rocks at surface (Figure 4.14, top), has a rugged terrain along the southern part and varies in total about 600 m in elevation between the lowest and highest points. The terrain is most rugged at the expected Kaapvaal Craton-Tugela Terrane interface and point to possible remnants of a mountain range that existed in the past due to the docking event between the Tugela Terrane and the Kaapvaal Craton. The extracted total magnetic field (TMF) indicated by the broken grey coloured lines and has medium to large amplitude magnetic anomalies that can be simulated by mostly semi-vertical bodies.

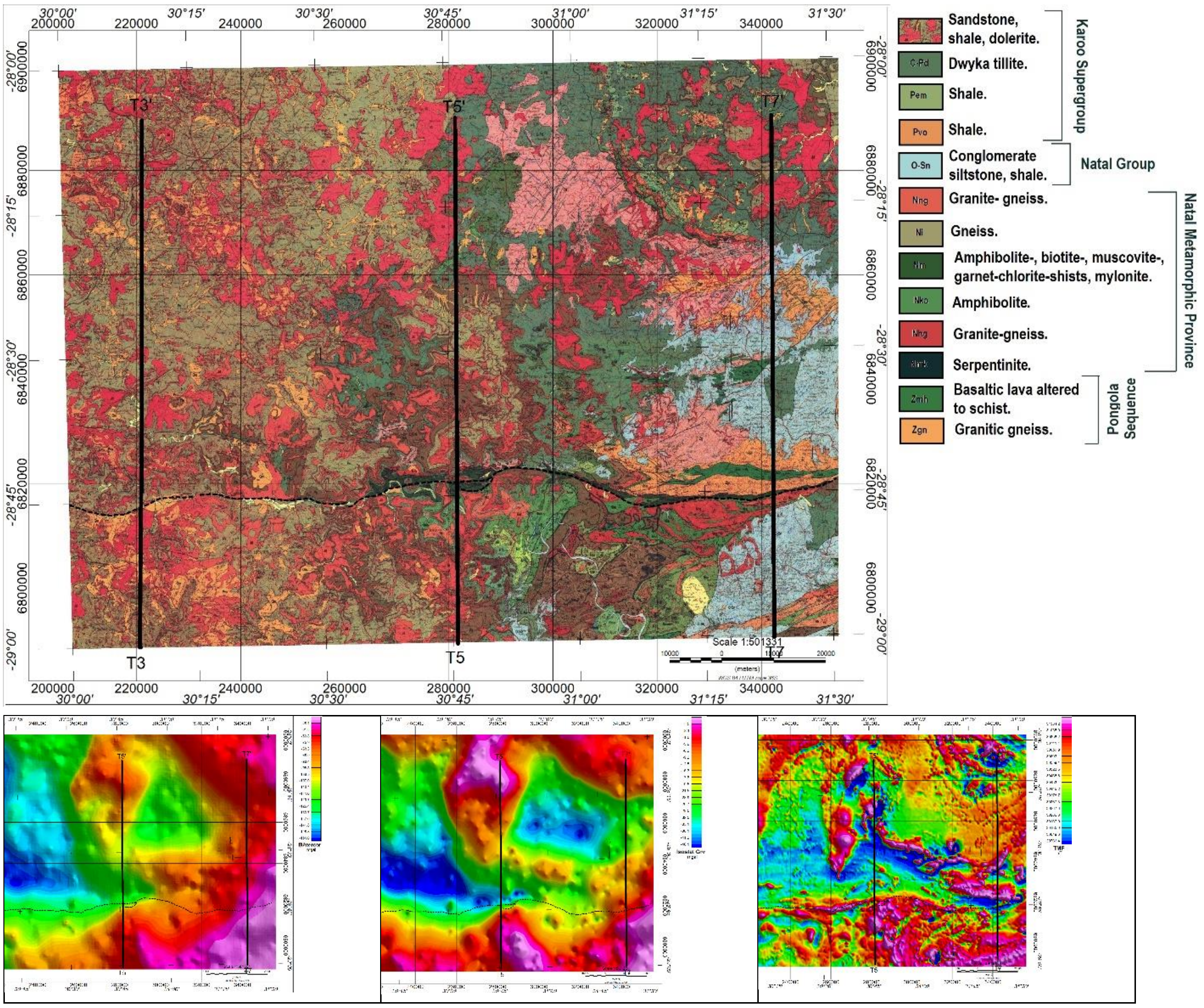


Figure 4.13. Top: *Excerpt from the 2830 Vryheid 1:250 000 scale geology map of the Council for Geoscience. The black vertical lines depict three traverses (T3, T5, T7) along which elevation, gravity and magnetic data were taken for modelling purposes. The black east-west curvy broken line depicts the expected faulted boundary between the Kaapvaal Craton, and Tugela Terrane inferred from the geological data.* ***Bottom:*** *Left is a colour coded image of the terrain corrected Bouguer Anomaly gravity data. Middle depicts the AH30 isostatically corrected gravity data. Right shows the total field regional aeromagnetic coverage.*

with a contrast to the non-magnetic background as indicated by the SI units as in the model below the data. The simulated (calculated) response of the model is shown by the solid black lines. The model was cut-off at a depth of 12.5 km below surface as extending the bodies below that depth has no influence on the amplitudes of the calculated TMF. Apart from the horizontal magnetic body in the centre of the traverse the southern boundary of which coincides with the expected edge of the craton the remainder of the bodies do not contribute to an improved understanding of the collisional zone. The horizontal body possibly indicates an accreted crustal unit.

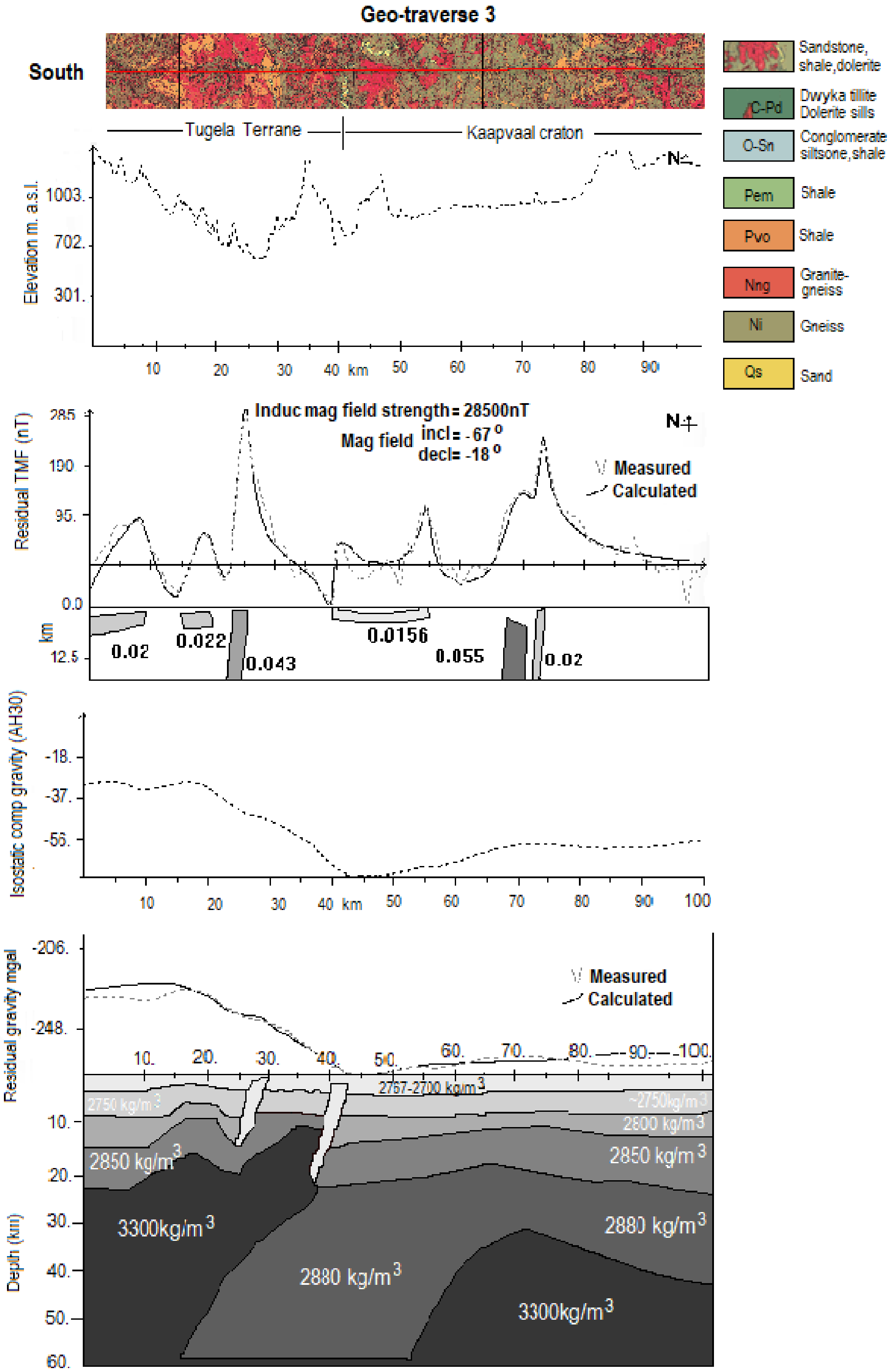


Figure 4.14. *Geo-traverse 3. Excerpt from the Council for Geoscience, Vryheid geological map followed by SRTM elevations below.* ***Middle:*** *Regional TMF with calculated response followed by AH30 gravity data.* ***Bottom****: BA gravity data and the postulated gravitational density model. Dipping Kaapvaal Craton crust into mantle material is reflected by negative isostatic anomaly. Two low*

density (2600 kg/m^3) semi-vertical bodies represent schists (Nm) that would allow stress release in an E-W and vertical direction.

The gravity data consist of the AH30 isostatically corrected gravity, and the terrain corrected Bouguer Anomaly (BA) values. The measured results show a distinct low in both the BA and AH30 values. The low in the isostatically corrected data indicate, barring a crustal dimension density low geological unit in the upper crust, that the crust extends into the mantle and that a topographical high that should have compensated for this crustal root is no longer present. In the past this was the mountain range that existed over the collision zone and has since been eroded. The BA values also show this gravity low, and it remains to formulate a model that simulates the measured response. This topographical and density imbalance causes the depressed crustal slab to experience an upward force that is negated by crustal forces probably emanating from mid-Atlantic oceanic ridge-push, holding the depressed crustal slab, pressed against the Kaapvaal Craton boundary, in place.

To model the BA values, the densities were taken with respect to the upper mantle density of 3290 kg/m^3. Furthermore, the regional field was chosen at a constant value of +230 mGal that is taken as what would have been observed should the dense mantle material have extended to the surface of the earth. The postulated gravity model consists of a crust with a gradational increase in density represented here by five layers of increasing density starting with a density of 2650 kg/m^3 at surface. Since geophysical models do not present a unique glimpse of the subsurface there are other similar models that can also simulate the measured results equally well, but the purpose here is to show that the original postulate is feasible and other variations in the gradational density increase are also possible if the measured gravity response is well simulated.

The model shows that the down dipping, to the south, Kaapvaal Craton crust and upward dipping accreted Tugela Terrane form the framework of the model as first postulated by Matthews (1972). De Beer and Meyer (1984) also show a similar model for the Kaapvaal Craton-Natal Metamorphic Province interface except that the crustal mantle interface is at about 22 km and the crustal depression into the mantle is less severe, but the isostatic anomaly data was not available, and our model is not unique.

It is notable that two low density (2600 kg/m^3) semi-vertical bodies, probably representing the multitude of schists, denoted as Nm on the Vryheid geology map (see top of Figure 4.13) must be added to achieve the local low gravity signature and that this material in this context occurs to a depth of 15 and 20 km. The presence of that material would allow stress release in a E-W and possibly vertical direction.

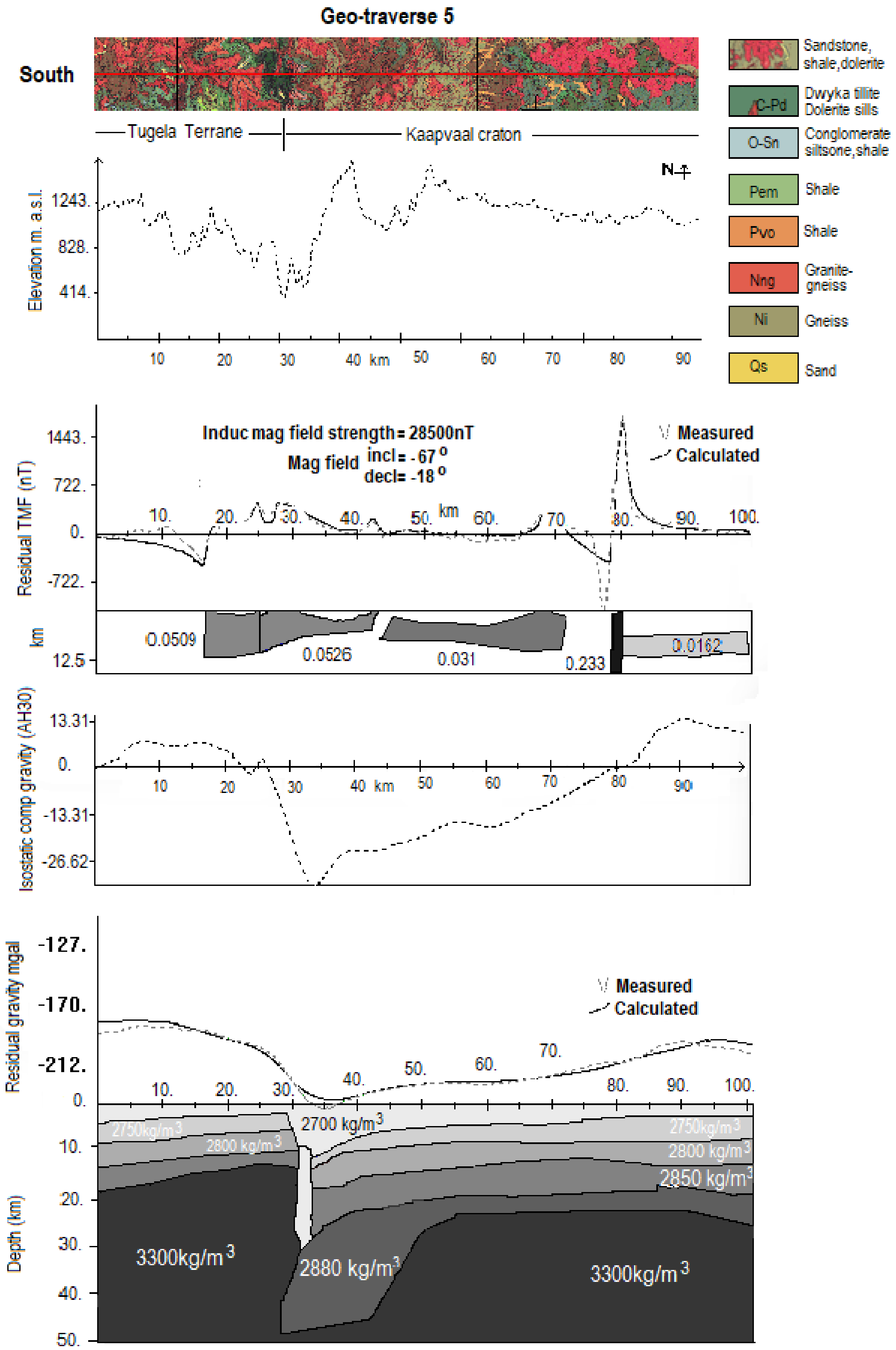


***Figure 4.15** Geo-traverse 5. Like Geo-traverse 3 (Figure 4.14) **Middle:** Regional TMF with calculated field that shows horizontal crustal units that do not align well with the crustal boundaries as expected from the geology. The AH30 gravity data response has a very sharp negative signature. **Bottom**: BA gravity data and the postulated model. The vertical low density (2600 kg/m^3) body*

represented by schists (Nm) would allow E-W and possibly vertical movement to enable stress release.

Geo-traverse 5 is the central one and depicted in Figure 4.13 and shows rugged terrain north of the expected Kaapvaal Craton–Natal Metamorphic Province (NMP) crustal boundary. There is also a very subdued magnetic response indicating the boundaries of crustal blocks that except for one do not readily coincide with the boundary given by the geology. Similar results were obtained than along geo-traverse 3 except that the isostatically compensated gravity values show a more pronounced gravity low. The addition of the vertical low-density body is needed to simulate the BA gravity measurements, but close inspection of the model shows that a greater volume of this material can still be added to better simulate the measured BA response.

Geo-traverse 7 is the most eastern one and is given in Figure 4.13. It has a wide variety of geological units at surface and represents a deeper section of the geology than below the extensive Karoo cover on Traverse 3. Rugged terrain varying between 500 and 1100 m above sea level is present along the traverse. The aeromagnetic data shows the signatures of highly magnetic geology of which the most southern one coincides with the expected southern boundary of the Kaapvaal Craton. The magnetic field can be simulated with three semi-vertical bodies with magnetic susceptibilities varying between 0.1 and 0.2 SI units.

The isostatically compensated gravity values show a complex double low which probably relates to two crustal slabs being depressed into the mantle as shown in the model and the crust mantle boundary depth varying between 17 and 35 km. No low density semi-vertical bodies are necessary to be included in the model and the black vertical bodies are the magnetic bodies superimposed on the gravity model.

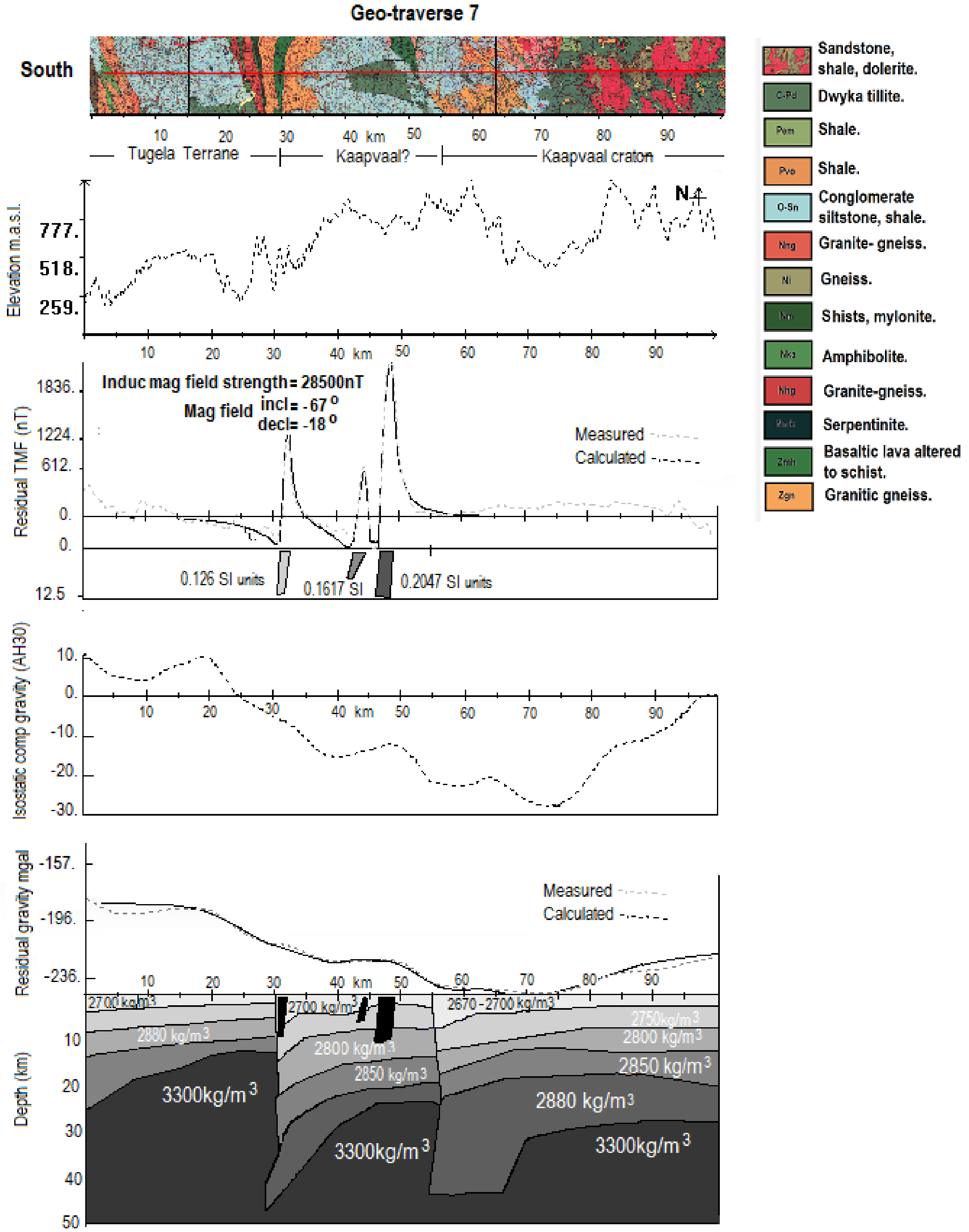


Figure 116 *Geo-traverse 5. Excerpt from the CGS, Vryheid geological map followed by SRTM elevations below.* ***Middle:*** *Regional TMF with calculated response followed by AH30 gravity data.* ***Bottom****: BA gravity data and the postulated model which needs two crustal sections dipping into the mantle material to simulate the measured gravity data. No low-density vertical bodies are needed to reproduce the gravity measurements, but the vertical black bodies reflect the very high*

susceptibility magnetic bodies, of which only one coincides with the Kaapvaal Craton crustal boundary.

4.5 Synthesis of the tectonic model and conclusion

On the 16th of June 2015, KwaZulu-Natal was struck by an earthquake whose epicentre was in Sundumbili. This earthquake generated a lot of interest in the media and on various social media platforms because of the damage that was caused. The University of KwaZulu-Natal undertook a macroseismic survey to investigate the effects of the earthquake within the province. The epicentre of the earthquake was within the imbricate thrust zone of the Tugela Terrane and the southern flank of the Kaapvaal Craton. Sulphur hot springs can be found in this area and a minor volcanic eruption was also reported in 1983. This evidence strengthened the work of Jacobs and Thomas (1994) who suggested that tectonic activity is still taking place in this area and that pre-existing zones of weakness are undergoing reactivation. Our models show that dense rocks (which may include upper mantle) could reach up to a depth of 17 km along the Kaapvaal Craton - Tugela Terrane along geo-transect 3 indicating a shallower heat source. This is of importance to green energy investigators.

Although the seismicity map of KwaZulu-Natal province shows diffuse seismicity, a prominent NE trend characterised by minor earthquakes can be seen in the southern part of the province. Similarly, a NW trend in the northern part of the province is noticeable. However, in the central part of the province where the Kaapvaal Craton Tugela terrane boundary occurs there is a E-W trend of earthquakes of low to moderate magnitudes that are recorded by the present IMS network but were also already recorded pre-1970 before the instrumental seismic network for South Africa was formally established and sparsely distributed contemporary seismic events were then recorded by a few seismographs installed in the major cities.

A visual inspection of the regional geology indicates an abundance of pyroxenite, amphibolite, biotite muscovite, sericite schists along the central part of the Tugela fault that would facilitate movement along the fault. The total field aeromagnetic data shows magnetic high amplitude anomalies both north and south of the Tugela fault, but only occasional on the fault itself. The highest amplitudes are south of the fault. The anomalies do point to crustal bodies with differing magnetic susceptibilities both north and south of the fault. Using the Airy-Heiskanen root, anti-root principle the isostatically compensated gravity map shows a clear negative anomaly along the strike of the Tugela fault indicating that the present topography over the fault lacks the height to compensate for the present crustal root and that due to the collisional docking event that resulted in the Natal Metamorphic Province created by a past topography that was much higher and extensive as evidenced by the deeper than predicted 'roots' in our models, that are now not compensated by the overlying topography as reflected by substantial negative isostatically compensated gravity anomalies of up to -50 mGal.

The terrain corrected Bouguer anomaly gravity data shows similar signatures and using a gradational increase in density from surface (2650 kg/m^3) to the Moho interface (2880 kg/m^3) as constrained by seismic velocity models, the crust can be shown to exhibit a root of crustal material pressing into the upper mantle. The lack of compensating topography as indicated by the negative isostatic gravity anomaly and 15% density contrast between lower crust and upper mantle would cause a buoyancy in the lower crust and an impetus of the lower crust to ‘bounce back’ with a resulting upwards movement. However, it is expected that this is mainly held in check by the NE directed oblique ridge-push of the mid-Atlantic oceanic ridge on the southern African plate.

The modelling of the gravity and magnetic data agrees with the postulate of an oblique collision that led to a mountain building process of which the Natal Metamorphic Province is a crustal remnant whereby crust of the previous Rodinia crust was obducted onto the Kaapvaal Craton. The obducted rocks are ophiolites that today act as a lubricant to permit steady creep and relieve tension due to oblique compression from the Mid-Atlantic Ridge and the incipient rifting from the East African Rift System. The NE-SW orientation of the seismic events in the area also supports the direction of movement of the Natal Metamorphic Province against the Kaapvaal Craton. This movement is also in agreement with geodetic studies by Malservisi et al. (2013) who concluded that the east coast is undergoing internal deformation that is greater than in other parts of South Africa. The NE-SW trend aligns well with the movement of the East African Rift System as well as the ridge-push forces from the Mid-Atlantic Ridge which pushes the African plate in a similar direction. Jacobs et al. (1993) also suggested that large increments of transcurrent strain were accommodated along the old transform margin, forming the Lilani-Matigulu Shear Zone during later sinistral shearing.

An interesting feature that was observed in this study was the pronounced negative anomaly at the southern margin of the Kaapvaal Craton and Natal Metamorphic Province. This suggests that these two are not in isostatic equilibrium and would imply that the less dense Kaapvaal Craton is pressing down into the denser mantle. Such an occurrence is analogous to a wine bottle cork being pushed into water which under normal circumstances leads to it shooting upwards. The explanation for this is that due to the collision, a huge mountain range existed in the past that was supported by deep roots pressing into the mantle. The mountain range has since been eroded, but the roots remain, trapped by the oblique pressure exerted from the Mid-Atlantic Ridge and East African Rift System in a NE-SW direction. To release the pressure, deformation happens in a E-W and NE-SW direction along suitable fault lines lubricated by serpentinite along the suture zone. If this is the case, then one would expect to see seismic events of a greater magnitude in this area.

The sparsity in seismic activity along the Tugela fault is interpreted as being due to the slippage occurring more smoothly along the fault and its extension towards the east. However, in areas north and south of the fault where favourable ophiolitic material is not present slippage is not smooth and occurs by many small magnitude events. The serpentinite, which is common in active geologic settings, also possibly lubricates the movement of the Natal Metamorphic Province over the Kaapvaal Craton thereby permitting steady creep particularly as the shear stress is low. That said, according to Hirth and Guillot (2013), depending on temperature, normal stress, fluid pressure, and deforming thickness, a range of unpredictable behaviours can occur if velocity increases in transform boundaries. Also, steady creep is dependent on the proportion of serpentinite, and according to Fagereng and MacLeod (2019), as little as a 9% decrease in serpentinite may lower the strength of the aggregates to that of pure serpentine. Rehydration of serpentinite which leads to weakening and strain localisation is also a known and accepted mechanism that has been used to account for intermediate-depth earthquakes (Raleigh and Paterson, 1965; Hacker et al., 2003). These factors are unknown in KwaZulu-Natal and further highlight knowledge gaps that require further studies. Fortunately, the deformation rates are small which therefore slows down the pressure build-up.

Several insights come to the fore from this study. The sparsity of seismic monitoring stations in KwaZulu-Natal needs to be addressed to understand potential sources of seismic activity in the province. It is clear from the macro-seismic survey reports that KwaZulu-Natal is susceptible to the occurrence of tsunamis. This has been highlighted by the effects of the 31 December 1932 earthquake and studies by Kijko et al. (2018). This study also highlights that multi-disciplinary collaboration between seismologists, geologists and geophysicists can improve the understanding of the seismotectonic setting of South Africa.

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Chapter 5: Seismic velocity distribution and crustal structure of KwaZulu-Natal inferred from gravity data.

5.1 Introduction

Understanding the crustal structure sheds light on crustal evolution and the physical properties of the crust. The physical properties of the lithosphere regulate mantle convection, the rate at which heat is released to the Earth's surface, the general rules that define plate tectonics as well as the location of earthquakes and volcanoes (Wright et al., 2004; Mooney, 2015). Intraplate earthquakes, for example, are prone to occur in the vicinity of lithospheric thickness gradients particularly at craton boundaries (Mooney et al., 2012; Tesauro et al., 2015). Seismological data is commonly used to derive crustal structure models. South African research agencies have conducted projects to study the crustal structure of the country, such as the South African Seismic Experiment (Carlson et al., 1996).

These studies have not sufficiently covered KwaZulu-Natal due to the sparsity of seismic data e.g. Nguuri et al. (2001) and Delph and Porter (2015). In Figure 5.1 it can be seen that there is no data coverage along the east coast of South Africa at the boundary of the southern edge of the Kaapvaal Craton and northern edge of the Namaqua Natal Belt (NNB). This study sought to plug this gap using available gravity data. This approach is a useful complementary tool for interrogating crustal structure models obtained from seismic data. Supplementary data to support and verify seismic models are essential, as it may be misleading to hinge our knowledge of Archaean crustal formation processes only on seismic data, particularly if the crust has undergone significant tectonic events such as rifting or accretion (Delph and Porter, 2015).

Using travel times of earthquake data, Hales and Sacks (1959) suggested that the eastern Kaapvaal Craton has a two-layered crust with a thickness of 36.6 km. In a global study, Durrheim and Mooney (1991) compared Archaean and Proterozoic provinces. They concluded that the crust that stabilised in the Proterozoic is substantially thicker (40 to 55 km) than the crust that stabilised in the Archaean (27 to 40 km) and has a greater composition of material with seismic velocity greater than 7 km/s. They did not find evidence of a high velocity crust as proposed in earlier seismic studies.

Using seismology data, Durrheim and Green (1992), Nguuri et al. (2001), Wright et al. (2004) as well as Delph and Porter (2015) also concluded that the Archaean Kaapvaal Craton is thinner than the Namaqua-Natal Metamorphic Province. Several seismic studies have revealed that the Kaapvaal Craton has a largely felsic composition whereas the Natal Metamorphic Province has a mafic lower crust (Kgaswane et al., 2009; Delph and Porter, 2015). Green and Durrheim (1990) found the Proterozoic Natal Metamorphic Province to largely consist of rocks with a crustal velocity of between 6.2 to 6.9 km/s. Their results were from a 290 km seismic refraction profile extending from Kakamas to Springbok. Using the coherence technique, Doucouré et al. (1996) calculated the effective elastic thickness of the Kaapvaal Craton and Natal Metamorphic Province. They found the elastic thickness to be 72 km and to have a range of 38 to 48 km for the Natal Metamorphic Province. These differences were attributed to compositional and thickness differences of the lithosphere between the two tectonic provinces as well as asthenospheric heat flow. Green and Durrheim (1990) proposed similar ideas to explain the differences in crustal structure between the Kaapvaal Craton and Natal Metamorphic Province.

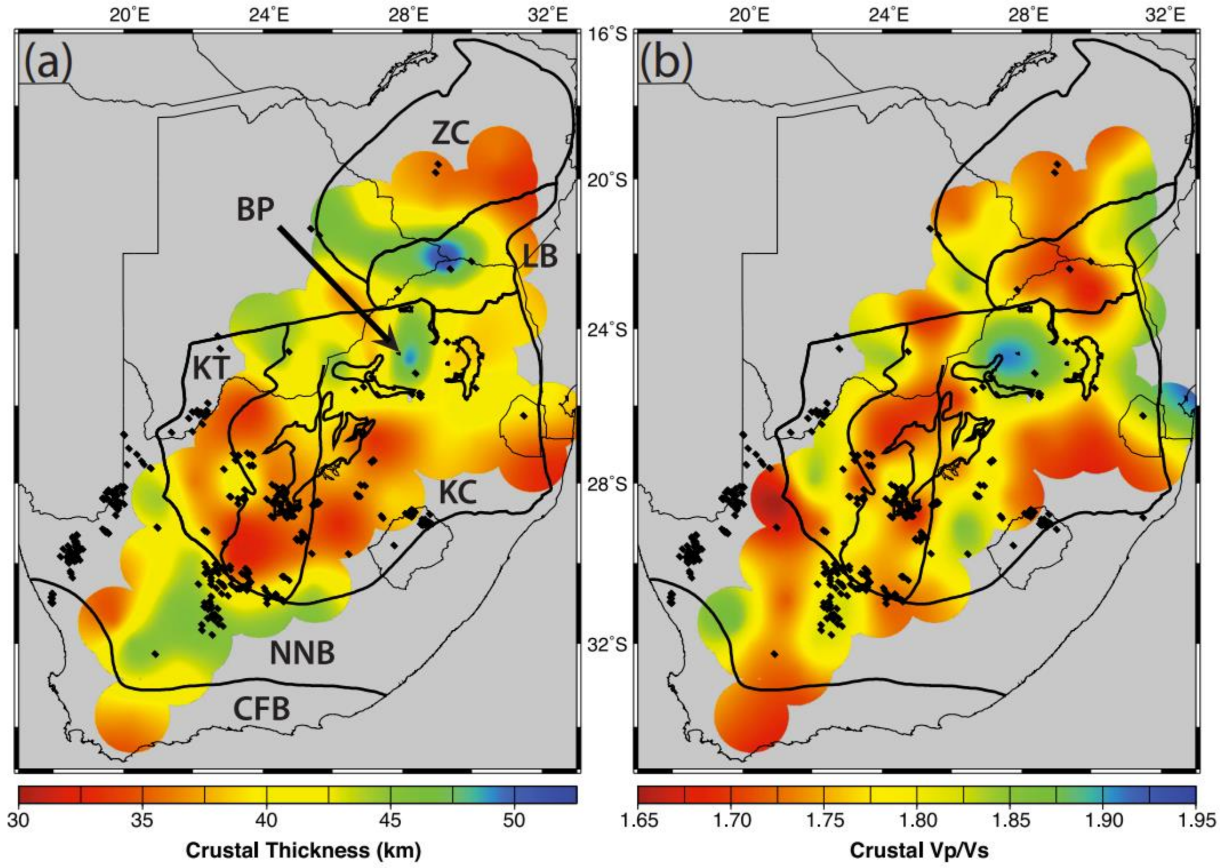

Figure 5.1 *(a) Crustal thickness and (b) crustal Vp/Vs map of southern Africa according to Delph and Porter (2015).*

Qiu et al. (1996) studied the lithospheric structure of the Kaapvaal Craton using selected seismograms of regional and teleseismic earthquakes. They concluded that the Kaapvaal Craton consisted of a 42 km four-layer crustal structure with a 2 km thick 5.05 km/s surface layer, a 5 km thick 6.0 km/s upper crust, a 20 km thick 6.30 km/s mid-crust and a 15 km thick 6.73 km/s lower crust. Kgaswane et al. (2009) jointly inverted receiver functions and Rayleigh wave group velocities and found the lower crust to be mainly mafic with a shear wave velocity that is greater than 4 km/s.

5.2 Geology of KwaZulu-Natal

The Archaean Kaapvaal Craton and Mesoproterozoic Natal Metamorphic Province form the foundational geologic units of KwaZulu-Natal. The southern margin of the Kaapvaal Craton is a granite-greenstone terrain (De Beer and Meyer, 1984). The Natal Metamorphic Province flanks this margin of the Kaapvaal Craton and forms part of a Grenville orogenic belt. Karoo Supergroup rocks are found in the central part of the province. They extend towards the Drakensberg in the west. The coast largely consists of younger Cenozoic Zululand Group sandstone.

It has been suggested that the Natal Metamorphic Province was formed as a result of the convergence of the Kalahari and Laurentia during the formation of the supercontinent Rodinia (Delph and Porter, 2015). It extends laterally eastwards from southern Namibia, through Namaqualand under Phanerozoic cover into KwaZulu-Natal (Mendonidis and Graham, 2003; Mendonidis et al., 2015). The Natal Metamorphic Province may be divided into two parts in South Africa. The eastern portion is normally referred to as the Natal Metamorphic Province in KwaZulu-Natal whereas the western portion is named the Namaqua Metamorphic Province in Namaqualand.

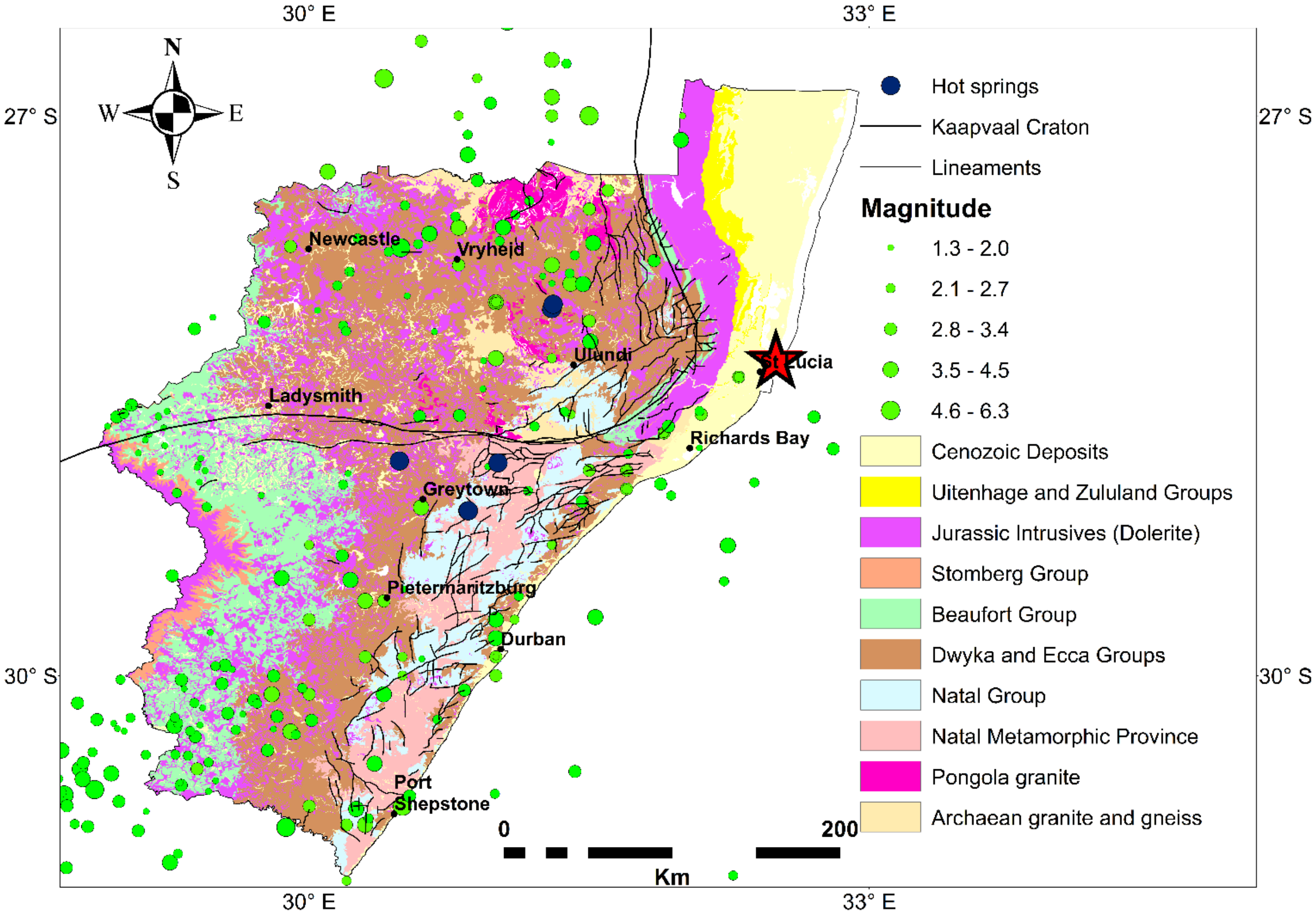

Figure 5.2 *Generalised geological units of the KwaZulu-Natal region at a scale of 1:250 000 (data from Council for Geoscience) with seismicity and faults overlaid on it.*

Thomas (1989) divided the Natal Metamorphic Province into three distinct tectonostratigraphic terranes, namely, from north to South: the Tugela, Mzumbe and Margate Terranes. The Lilani-Matigulu Shear Zone (LMSZ) separates the Tugela and Mzumbe Terranes while the Melville Shear Zone separates the Mzumbe and Margate Terranes. The Tugela Terrane consists of a thrust sheet, representing remnant of the Tugela Ocean. It has transported assemblages of mafic, ultramafic lavas and hypabyssal rocks (Thomas and Eglington, 1990; Mendonidis and Graham, 2003). The

Mzumbe Terrane is comprised of the Quha and Ndonyane Formations. The Quha Formation has the older rocks which are amphibolite grade layered gneisses and migmatites while the younger rocks of the Ndonyane Formation are fine grained gneisses (Thomas, 1989; Clarke, 2008).

The Natal Group is Ordovician (~490Ma) according to ^{40}Ar/^{39}Ar dating results of Thomas et al. (1992b). It is in contact with the Natal Metamorphic Province and consists of two formations which are approximately 600m thick. These are the lower Durban Formation as well as the upper Mariannhill Formation. The sedimentary rocks found in the Natal Group are greyish conglomerates, sandstones, siltstones and shales (Marshall and von Brunn, 1999; Hicks, 2010). The Karoo Supergroup ranges from Palaeozoic to Mesozoic age and outcrops in approximately two-thirds of southern Africa (Selden and Nudds, 2012). The rocks are mainly shales and sandstones. The Zululand Group is comprised of the Makatini, Mzinene and St Lucia Formations. It is well exposed on the western shores of St. Lucia, eastern Lebombo foothills, Phongola and Mkhuze River valleys (Kennedy and Klinger, 1975). These three formations contain conglomerates, sandstones, siltstones, and limestones. Cenozoic sediments form a thin covering that overlies the Zululand Group in the northern KwaZulu-Natal coastline (Dingle et al., 1983).

5.3 Gravity data and applied process

Geophysical methods are a useful tool for understanding the physical properties of the Earth's subsurface. In gravity surveys, subsurface geology is investigated based on density contrasts between rocks (Kearey et al., 2002). The data used in this study was extracted from the Council for Geoscience's South Africa regional gravity survey data (Venter et al., 1999).

The data were collected at an approximate station spacing of 14 km using La Coste-Romberg gravimeters. Earlier elevation measurements were determined using micro-barometers and in the 1990s the Global Positioning System (GPS) was used for this task. The measurements were tied to the International Gravity Standardisation Net values. Free-air and Bouguer corrections were computed according to the 1967 geodetic reference system. The density used for the Bouguer correction was 2.67 g/cm^3. The Bouguer gravity ranged from -188 to 81 mGal (Figure 5.3).

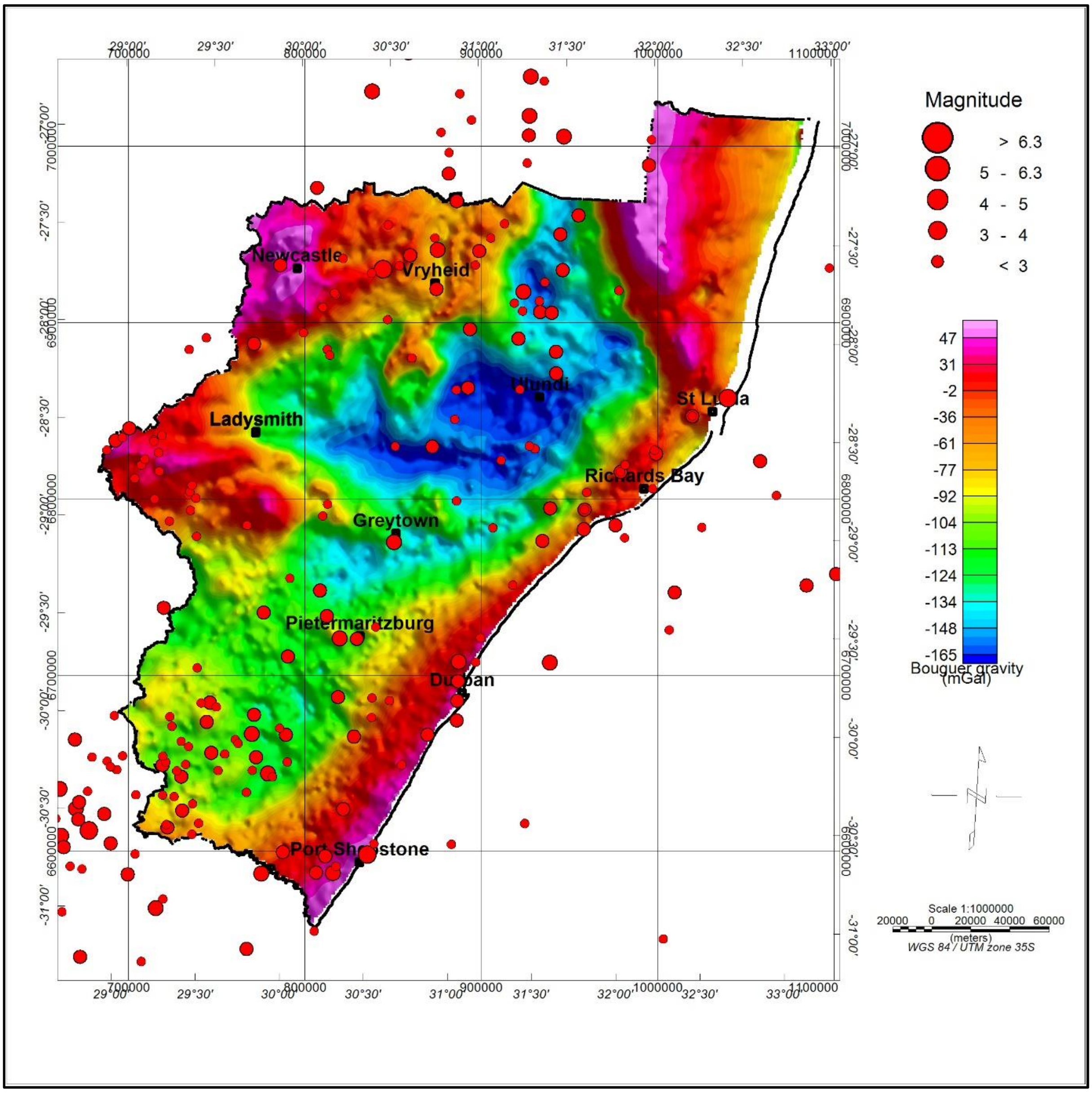

Figure 5.3 *Bouguer gravity map of KwaZulu-Natal with seismicity overlaid on it.*

A Butterworth high-pass filter of 1000 km was applied to the Bouguer gravity data to remove the contribution of deep lying mantle sources resulting in gravity residual anomalies that approximate crustal sources (Leseane et al., 2015; Chisenga et al., 2020). Gravity anomalies have proven to be a useful tool for inferring crustal thickness e.g., (Worzel and Shurbet, 1955; Woollard, 1959; Hales and Gough, 1959; Riad et al., 1981; Riad and El Etr, 1985; Rivero et al., 2002; Tirela et al., 2004; Akin, 2016; Bilim et al., 2021).

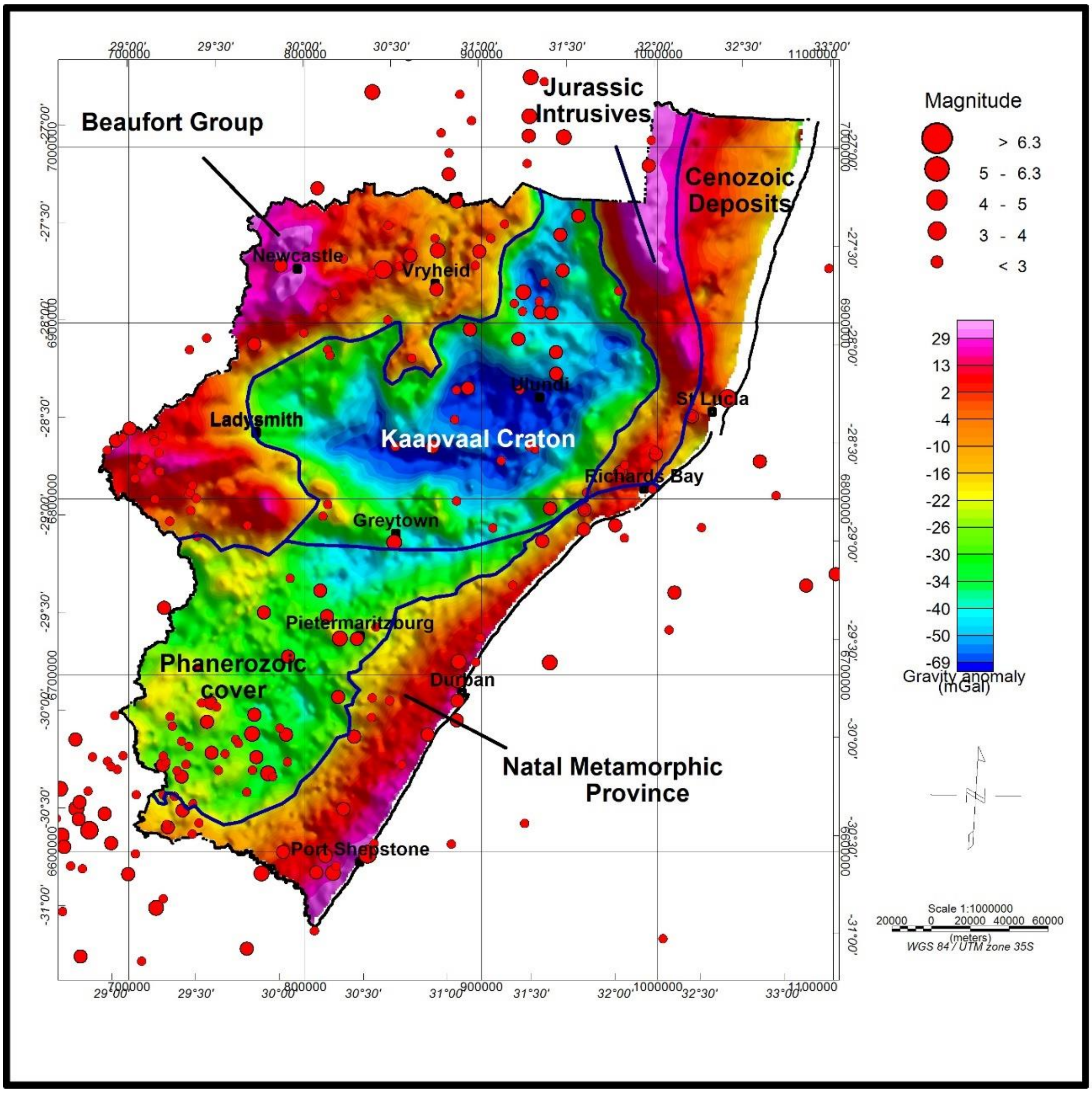

Figure 5.4 *Bouguer gravity anomaly map of KwaZulu-Natal with 1000 km high-pass filter applied and seismicity overlaid (Interpreted tectonic terrane boundaries are shown in blue).*

The empirical relation of Riad et al. (1981) was applied to calculate the crustal thickness of KwaZulu-Natal (Figure 5.5) .

$$T = 29.98 - 0.075\Delta g \qquad (5.1)$$

where T is the crustal thickness (in km) and Δg are the gravity anomaly values (mGal). The thickness of the KwaZulu-Natal crust as derived from the gravity data

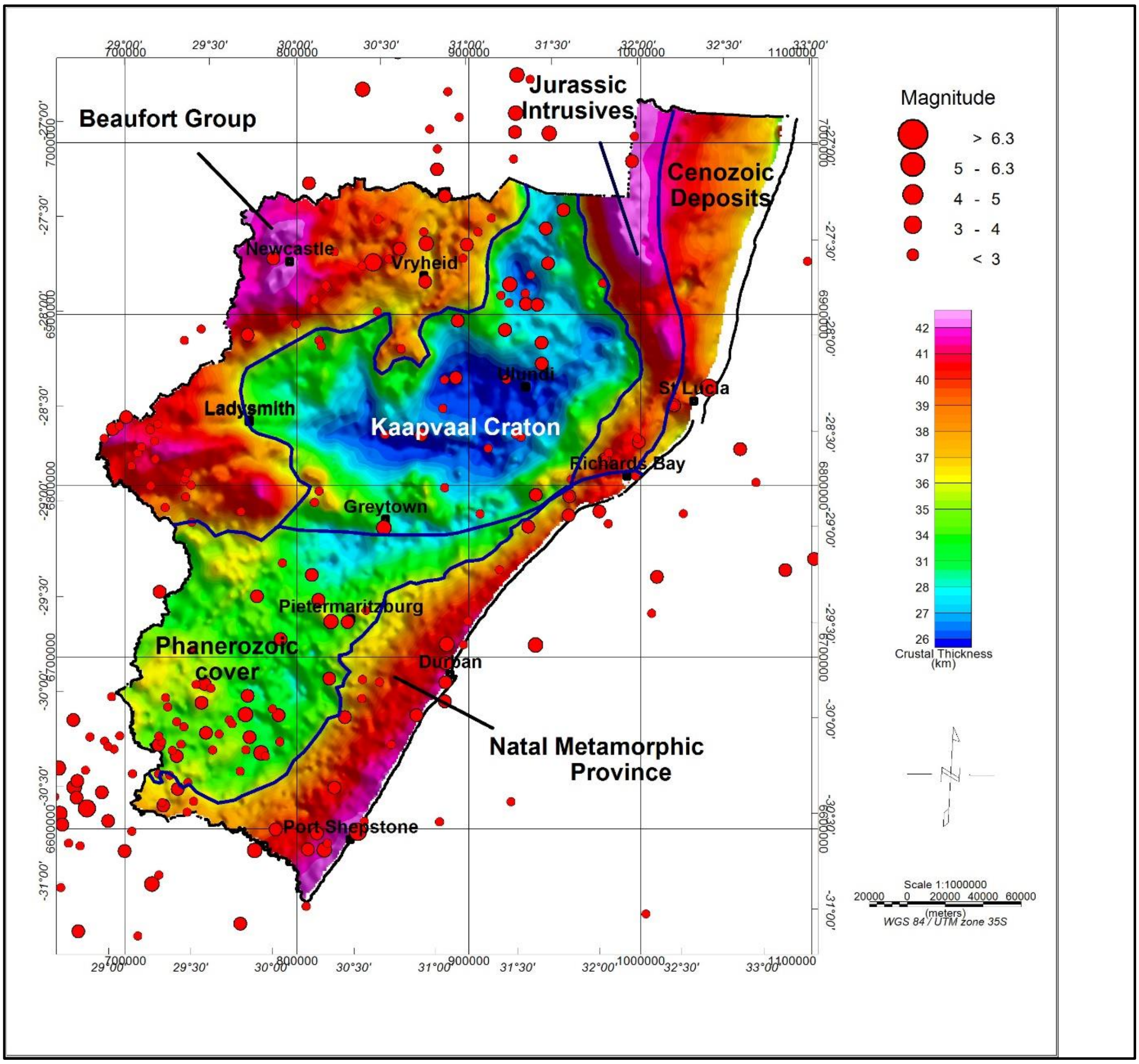

Figure 5.5 *Gravity derived crustal thickness map of KwaZulu-Natal with seismicity overlaid on it.*

ranges from 24 to 45 km. The crust is thicker in Proterozoic and Phanerozoic age rocks than in the Archaean in the north of the province.

Isostasy is based on the idea that excess mass above sea level is supported by differential mass distributions at the base of the crust. At relatively shallow depths, isostacy is achieved such that mountains are balanced by underlying mass deficiencies and oceans by surplus mass (LaFehr and Nabighian, 2012). The isostatic correction is useful in accounting for changing crustal thickness and topographic load to highlight density contrasts within the crust.

Figure 5.6 shows the Airy-Heiskanen isostatic anomaly map corrected using an assumed sea-level crustal thickness of 30 km as reference, covering KwaZulu-Natal, with values ranging from -95 mGal to 52 mGal. An interesting observation from this map is the exposure of local relatively dense rocks in the Drakensberg Mountain range, west of the province, after removing the long wavelength effects from the Bouguer gravity. We also observe a sharp negative anomaly at the southern margin of the Kaapvaal Craton where the Natal Metamorphic Province obducts onto it. This suggests that the Kaapvaal Craton is not in isostatic equilibrium along this margin, implying that it is sinking into the denser mantle. Subsequently, since the Kaapvaal Craton is less dense than the mantle, then the mantle would in turn push it up.

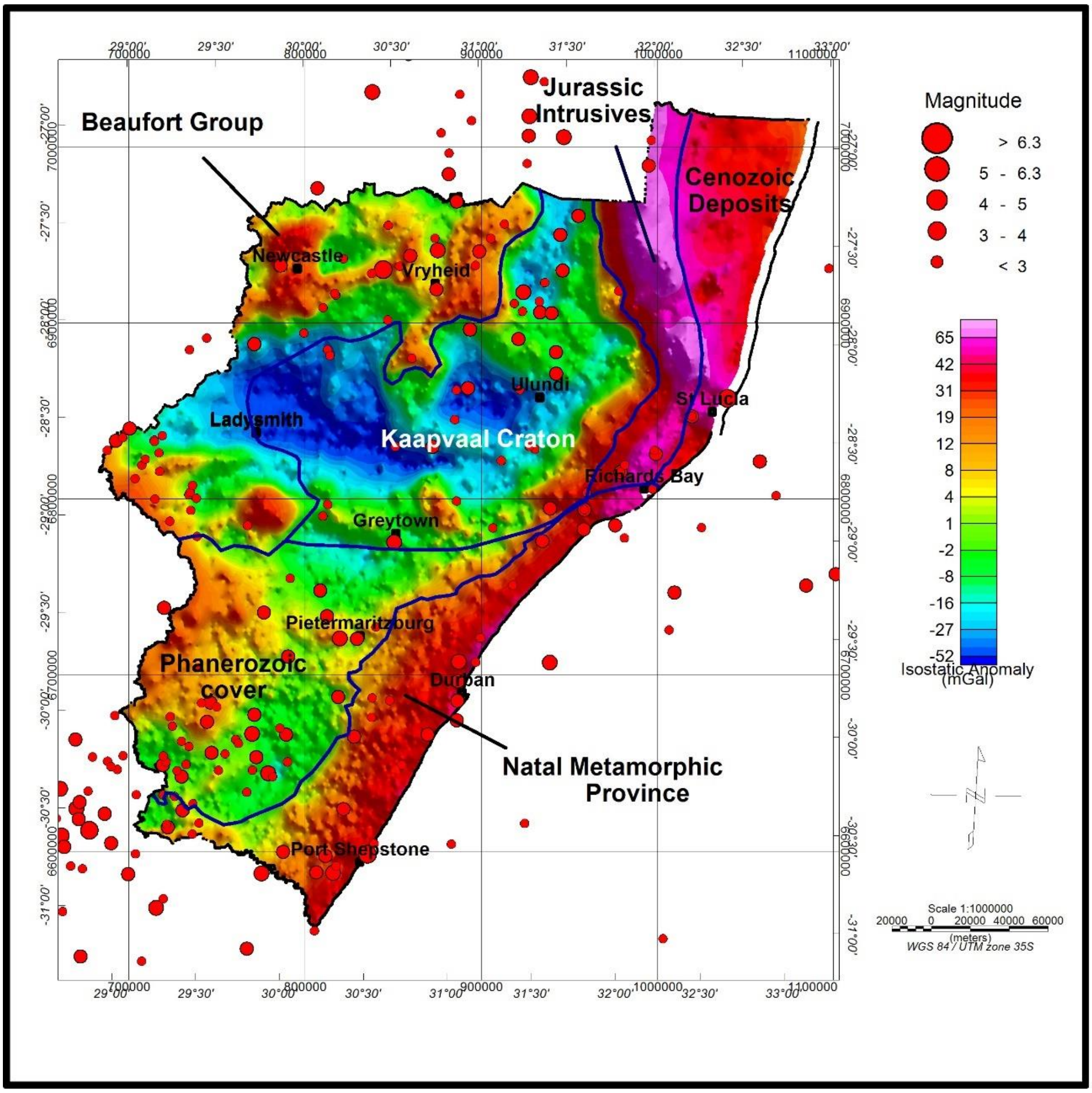

Figure 5.6 *Airy-Heiskanen isostatic anomaly map of KwaZulu-Natal with interpreted tectonic terrane boundaries in blue and seismicity overlaid on it.*

We applied an apparent density filter to the Bouguer residual gravity data as implemented in Oasis montaj software (Seequent, 2021).Gupta and Grant (1985) introduced the apparent density filter which is a valuable tool for assigning average rock densities and delineating rock-unit boundaries. The apparent density values of KwaZulu-Natal range from 2.54 to 2.76 g/cm^3 (for the 20 km depth slice). The density of the crust appears to be high along the coast and in the west of the province. It is lowest at the Kaapvaal Craton and gradually increases southwards from the collision zone of the craton and Natal Metamorphic Province.

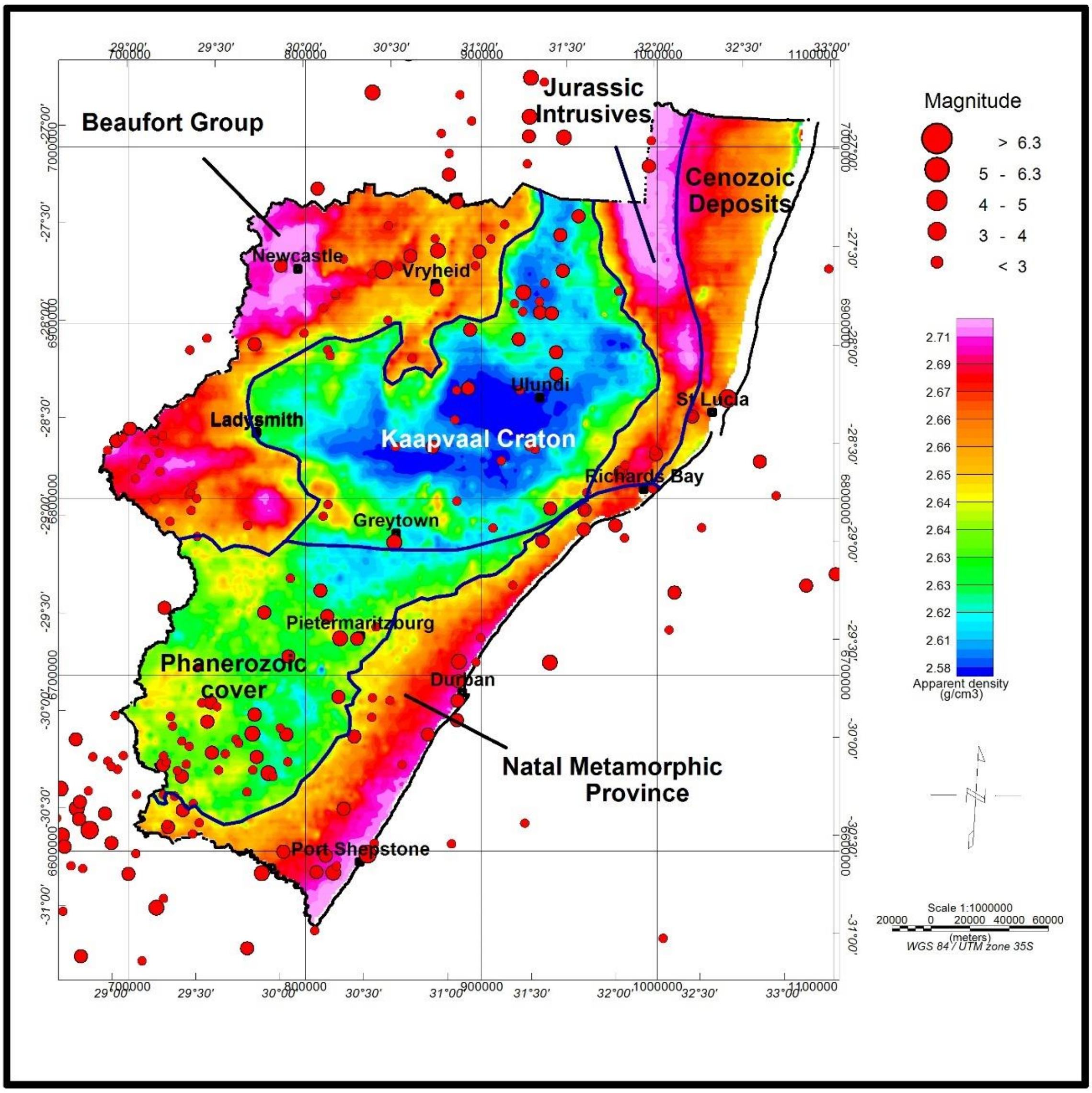

Figure 5.7 *Gravity derived apparent density map of KwaZulu-Natal with interpreted tectonic terrane boundaries in blue (measured at 20 km thickness) with seismicity overlaid on it.*

The velocity was generated by applying the empirical relation of Barton (1986),

$$\rho = 0.23v + 1.47 \tag{5.2}$$

where ρ is density in g/cm^3 and v is the *P*-wave velocity in km/s. The resulting 20 km depth slice map of the crustal *P*-wave velocity is shown in Figure 5.8 below.

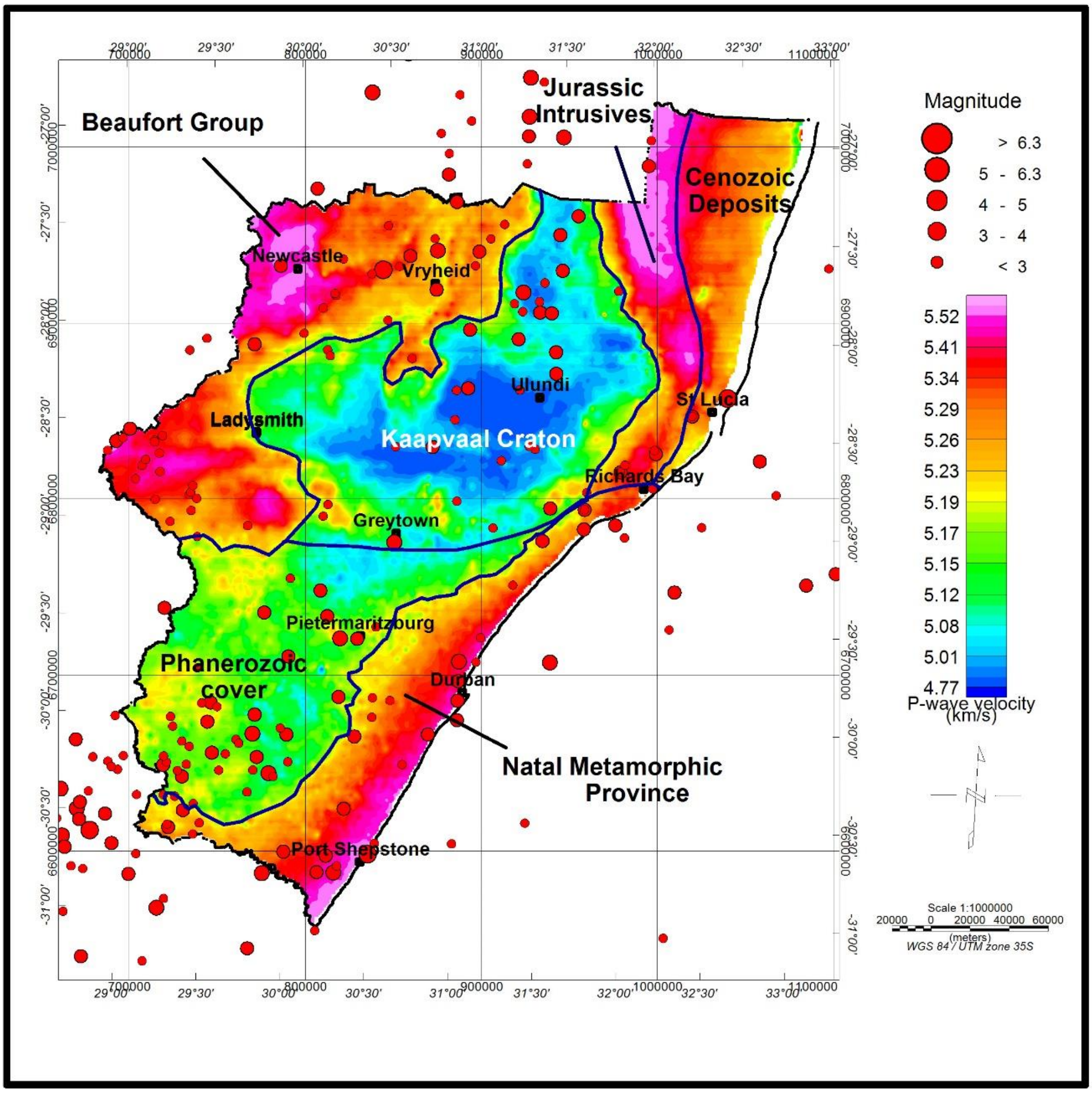

***Figure 5.8** P-wave seismic velocity map of KwaZulu-Natal with interpreted tectonic terrane boundaries in blue (measured at 20 km thickness).*

The *P*-wave seismic velocity for the 20 km depth slice ranges from 4.77 to 5.71 km/s. It is lowest at the Kaapvaal Craton and gradually increases southwards from the collision zone of the Kaapvaal Craton and Natal Metamorphic Province. The mean seismic wave velocities are lowest at depths of 0 to 11 km depth. However, an increase is observed from 11 to 31 km and a further increase beyond this depth (Figure 5.9).

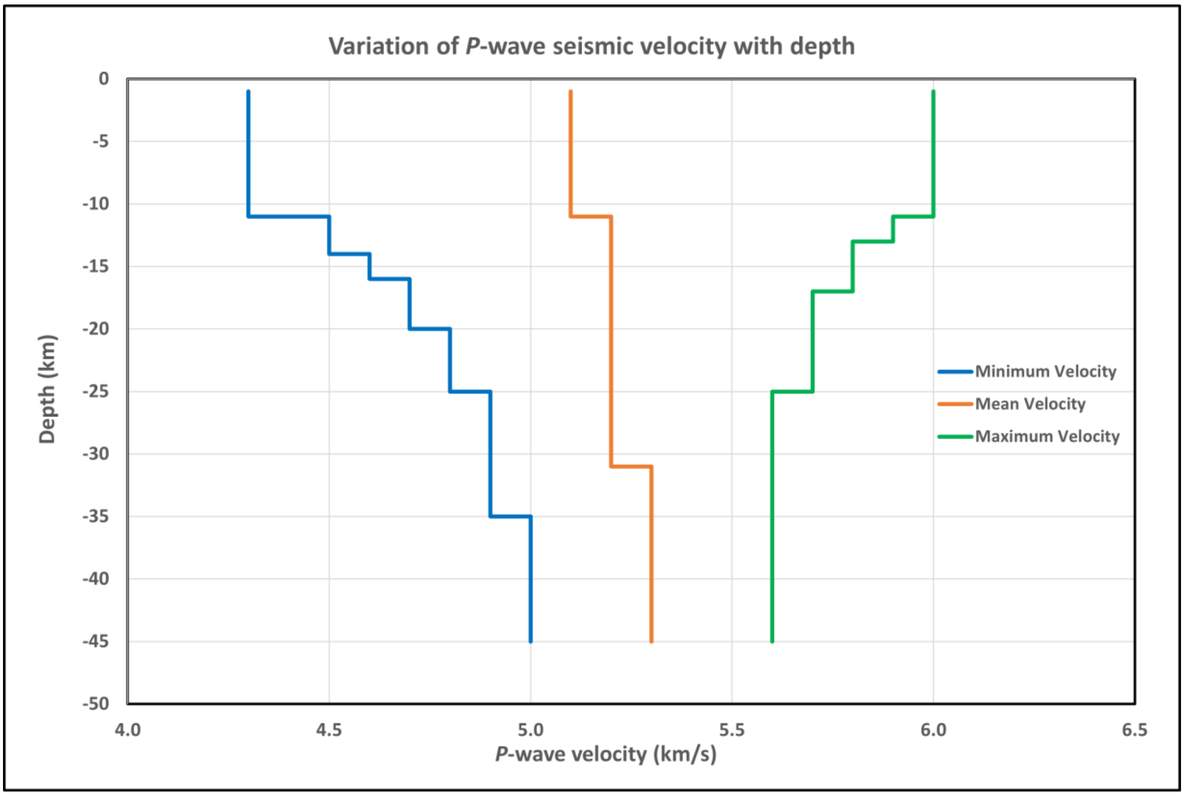

Figure 5.9 *Variation of P-wave seismic velocity at depths of 0 to 50 km for KwaZulu-Natal.*

To further investigate the depth at which high velocity and density values were observed, the thicknesses in the apparent density filter were linearly incremented as 1 km. It was observed that the boundary, where the maximum velocity and density were observed, was nearly at a depth of 41 km for KwaZulu-Natal.

5.4 Discussion

The Archaean Kaapvaal Craton was observed to have lower *P*-wave velocities and apparent densities compared to the Proterozoic and Phanerozoic crust. This may suggest that different crust forming processes have occurred during the Earth's history. According to Delph and Porter (2015), the velocity ratio V_p/V_s of the southern Kaapvaal Craton is approximately 1.73, implying that its composition is largely felsic. It would then be expected to observe lower apparent densities in the felsic Archaean Kaapvaal Craton compared to the mafic/ultramafic Proterozoic and Phanerozoic crust (Basson, 2000).

The results also show a direct correlation between crustal thickness and *P*-wave velocity with the seismic velocity increasing with crustal thickness. Drummond and Collins (1986) observed a similar correlation in Australia. They attributed this observation to the addition of basaltic underplated material at the base of the crust leading to a gradational velocity distribution. This possibility has also been suggested in global seismic-depth studies and in South Africa (Durrheim and Mooney, 1991; Durrheim and Green, 1992).

The mechanism that has been proposed in support of this by Durrheim and Green (1992) was that high temperatures in the mantle resulted in the eruption of ultramafic komatiite lavas. This led to a depleted mantle that was unable to generate sufficient basaltic material. This became an ideal place for Proterozoic crust to develop, resulting in basaltic underplating and crustal expansion.

5.5 Conclusion

This study showed that gravity can be a useful complementary technique to seismic methods in areas where there is a paucity of seismic data and works well as a tool for interrogating existing crustal structure models. KwaZulu-Natal has a sparse seismic network. This has resulted in seismic crustal structure models that do not encompass the province adequately. In this study, a seismic velocity distribution and crustal structure model for the province was derived.

The gravity-derived crustal thickness of KwaZulu-Natal ranges from 24 to 45 km. This is comparable to regional crustal thickness models derived from seismological data. The Archaean Kaapvaal Craton is thinner than the Proterozoic and Phanerozoic rocks, suggesting different crustal forming mechanisms. The difference in crustal thickness is attributed to the possibility of basaltic underplating.

The *P*-wave seismic velocities range from 4.77 to 5.71 km/s while the apparent density ranges from 2.54 to 2.76 g/cm^3. Much like the crustal thickness model, the Archaean Kaapvaal Craton has lower compressional wave velocities and apparent densities compared to the Proterozoic and Phanerozoic rocks. This is attributed to the felsic nature of the Kaapvaal Craton created by significant crustal modification related to the deposition of the Ventersdorp lavas consequently leading to lower apparent densities and compressional velocities.

Intraplate earthquakes are prone to occur in the vicinity of lithospheric thickness gradients particularly at craton boundaries. The Lilani-Matigulu Shear Zone which coincides with the southern margin of the Kaapvaal Craton is a known hotspot for seismic activity. The Lilani-Matigulu Shear Zone is also the site of hot springs and has been reported as the scene of a minor volcanic eruption. It also coincides with the neotectonic Quathlamba seismicity hotspot presently located at ~30°S and ~29°E (Gevers, 1963; Hartnady, 1990; Jacobs and Thomas, 1994). This suggests that tectonic activity along this shear zone is still happening to this day. In the crustal thickness map, we observe a crustal thickness gradient in this area. This suggests that there is a need for improved understanding of tectonic activity in the region to mitigate the effects of damaging earthquakes. These results can also form the basis of data driven seismotectonic modelling for Probabilistic Seismic Hazard Analysis (PSHA) as the seismicity pattern in the province correlates well with regions of varying geophysical properties.

Chapter 6: Discussion and conclusion

This study was aimed at understanding the seismicity and seismic patterns along the east coast of South Africa using geophysical and geospatial techniques. Earthquake seismology is a broad discipline that requires collaborative efforts between different disciplines to mitigate against loss of lives and damage to infrastructure due to earthquake occurrence. This study shows that KwaZulu-Natal, a fast-developing region with the second highest provincial population in South Africa, is characterised by moderate levels of seismicity. The province may also be vulnerable to tsunamis.

We paid particular attention to two earthquakes that originated from two sources and where macroseismic surveys were carried out following their occurrence. The 6 February 2016 earthquake originated from an offshore source, akin to the largest earthquake to have been recorded in KwaZulu-Natal, which was the M_L=6.3 event of 31 December 1932. The effects of the 6 February 2016 earthquake were widely felt within the province as well as in East London in the Eastern Cape province. Reports collected during a collaborative macroseismic survey between the Council of Geoscience and the University of KwaZulu-Natal revealed that this event led to damage of some structures. Interestingly, low-cost houses that were located further from the epicentre experienced damage from the earthquake while houses in affluent suburbs with well-built house did not experience any damage. This serves as an illustration of the importance of strict adherence to and enforcement of the national building codes on seismic loading in South Africa. If low-cost houses which are normally occupied by low-income households are not built to withstand the effects of seismic activity, then this leaves vulnerable people of the population who ought to be protected. Local site amplification effects originating from local geology were also observed because of this earthquake. It is commendable that the Council of Geoscience has recently undertaken studies to develop the understanding of local site amplification effects in KwaZulu-Natal through Multi-channel Analysis of Surface Waves (MASW) surveys. The University of KwaZulu-Natal is also presently undertaking studies to quantify the earthquake vulnerability of low-cost houses.

The United States Geological Survey reported a different epicentre than the one reported by the Council for Geoscience. This is attributed to the sparsity of seismic monitoring stations. According to Saunders (2017), the current configuration of the South African National Seismograph Network can only detect earthquakes with a local magnitude greater than three and is broadly designed to monitor mining-related seismicity and not tectonic earthquakes. The inability to detect microearthquakes hampers our understanding of seismic sources that may potentially affect the province and South Africa at large and also means that instrumental seismic catalogues are incomplete and are of an uneven quality. Manzunzu (2021) has recently shown that poor quality earthquake catalogues in South Africa are a source of significant uncertainties in seismic hazard studies.

The uncertainty in the location of earthquakes means that they cannot be reliably associated with specific active faults and are therefore treated in Probabilistic Seismic Hazard Assessment (PSHA) studies as area sources whose boundaries may not be well delineated, instead of linear sources.

This vague attribution needs to improve for these studies to be well constrained. There is also a need for a deliberate and concerted effort directed towards understanding physical processes that may be occurring in offshore sources, which is a key input in seismic hazard studies for the country. The deployment of offshore underwater seismic monitoring stations would also be a welcome development as this would assist in constraining the location of earthquakes along the coast.

The 2.5D gravity and magnetic models developed in this study support previously postulated geology models of oblique collision of the Natal Metamorphic Province leading to obduction of previous Rodinia crust onto the south dipping Kaapvaal Craton. This gives significant insights into the depth of seismic activity at the Tugela Terrane, which adds confidence to the delineation of earthquake source zones and provides constraints for the area characteristic maximum possible earthquake magnitude. The gravity and magnetic data have been correlated to seismotectonics in KwaZulu-Natal and this contributes significantly towards understanding seismic hazard and risk in South Africa.

The approach applied in this study may serve as a benchmark procedure of seismogenic source delineation. The modelling of gravity and magnetic data is relevant and applicable because the African plate is a stable continental environment where the driving mechanisms for earthquake activity are not fully understood because data that describes this type of activity is not available due to poor geodetic monitoring and low deformation rates. This study can be used as a template for understanding the earthquake mechanisms in active zones such as the Bongwana fault and the Ceres, Kango, Baviaanskloof, Coega (C-K-B-C) fault system in South Africa. This study focused on a smaller region than previous regional scale studies such as Singh (2016) and Manzunzu et al. (2019). The study of the crustal structure correlates with regional studies such as Kgaswane et al. (2009) and plugs gaps due to the lack of seismic data in KwaZulu-Natal available to calculate seismic velocity distribution.

The research objectives are revisited and discussed:

Gain insights into the seismotectonic setting of the east coast through the macroseismic survey of the 16 June 2015 and 6 February 2016 and KwaZulu-Natal earthquakes

The M_L=3.1 earthquake that occurred in Sundumbili on the 16th of June 2015 caused damage to the beach and fishing spot that is a source of sustenance to the local community. This earthquake shows that South Africa is vulnerable to the occurrence of a tsunami and this ought to be investigated. The source of the earthquake was at the southern margin of the Kaapvaal Craton and the Natal Metamorphic Belt. The earthquake provides evidence that seismic activity is occurring along pre-existing zones of weakness that are undergoing reactivation. This area is characterised by hot springs which are evidence of crustal fractures which are deposed to eventual reactivation.

Although deformation rates are low in this area as compared to, for example, the East African Rift System, it has been suggested that tectonic activity with compressive NE-SW movement is still taking place here and the Tugela fault is considered an active fault (Jacobs and Thomas, 1994).

The movement may be attributed to the East African Rift System and ridge-push forces from the oceanic ridges acting on the African plate. The long recurrence rate that characterises South African seismicity should not lull the population into dismissing threats in an intraplate region. The occurrence of the M_w=6.5 2017 Moiyabana earthquake in neighbouring Botswana should serve as a reminder that the country is not exempt from the occurrence of large events.

Define a local intensity attenuation model from macroseismic data

An intensity-based attenuation relation was developed for KwaZulu-Natal using macroseismic data from the 6 February 2016 earthquake. Such relations are useful as a constraint when selecting appropriate Ground Motion Prediction Equations (GMPEs) in seismic hazard analysis studies. This is because such studies allow one to compare intensity values to other regions with a similar tectonic setting. Although an accelerometer network has been deployed in South Africa recently, no large magnitude events have been recorded and there are still insufficient strong motion records at the near to intermediate distances (< 50 km) (Poggi et al., 2017) to develop a country specific attenuation model.

It has therefore been routine practice over the years to adopt attenuation relations from other similar tectonic regions for seismic hazard studies. The task of selecting appropriate attenuation relations is not to be taken lightly as it has been noted that the prediction of expected ground motion at a site is a major contributor to uncertainties in seismic hazard analysis (Budnitz et al., 1997; Stepp et al., 2001). The attenuation relation derived in this study appears to display a bias in attempting to fit both low and high-intensity values, which may be a result of local site effects. This implies that future seismic hazard studies for KwaZulu-Natal must account for local site effects due to geology, as these appear to markedly influence the behaviour of seismic waves in the province.

Build 2.5D model of the Natal Thrust Front based gravity and magnetic data to gain insights into the mechanism of seismic activity in this area

Fault geometry, rupture length, and slip rates of faults are not well known in South Africa. Despite this impediment, we have used publicly available data to glean valuable characteristics of the seismotectonic setting of KwaZulu-Natal. We incorporated multi-disciplinary data from seismology, geophysics, and geology to understand the possible mechanism of earthquakes occurring at the boundary of the southern margin of Kaapvaal Craton and the Natal Metamorphic Province. The modelling of gravity and magnetic data showed that the Natal Metamorphic Province obducted on to the southern Margin of the Kaapvaal Craton. The isostatic data shows that the Kaapvaal Craton is possibly sinking into the denser mantle as it is not isostatically compensated. This would also mean that earthquake foci in this area are not shallow but are likely to be of intermediate to deep seated.

Characterise the crustal structure of KwaZulu-Natal and how it influences seismicity in the east coast of South Africa

Gravity data was used to investigate the crustal structure of KwaZulu-Natal and calculate the seismic velocity distribution in the province. Previous studies have shown that intraplate earthquakes in stable continental regions, for example, are prone to occur in the vicinity of lithospheric thickness gradients, particularly at craton boundaries. The Kaapvaal Craton has lower crustal thickness than the Natal Metamorphic Province. The boundary of the two tectonic provinces is the Lilani-Matigulu Shear Zone which is a known hot spot for seismic activity in KwaZulu-Natal. The seismic hazard parameters for the suture at the Lilani-Matigulu Shear Zone need to be carefully evaluated through rigorous field work to identify individual active faults and paleoseismic events.

Gravity data was also used to calculate the seismic velocity and density distribution in KwaZulu-Natal. The results show a good correlation between geology, geophysics, and seismic data. According to Reiter (1990), differences in seismic wave velocities as well as anomalous linear magnetic and gravity gradients are clues for identifying geological faults. Results of this study can be used as an input into seismotectonic modelling. This work is important because in seismic hazard analysis, all possible sources of seismic activity must be identified and their potential to generate strong earthquakes in the future evaluated (Kramer, 1996).Future development should not disregard potential seismic risk in the region. Although the activity is relatively low compared to other regions in the world, the potential for earthquake magnitudes of up to 7.6 have been calculated in seismic hazard studies for KwaZulu-Natal (Midzi et al., 2020).

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