Mine Health and Safety Council

Fluid-Induced Seismicity in the Central Basin Area: Ground Motion Prediction and the Development of an Early Warning System for Risk Reduction

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ABBREVIATIONS AND NOMENCLATURE

- CLVD: Compensated Linear Vector Dipole
- DMR: Department of Mineral Resources
- DC: Double Couple
- ISO: Isotropic
- NEHRP: National Earthquake Hazards Reduction Programme
- MHSC: Mine Health and Safety Council
- MHSI: Mine Health and Safety Inspectorate regions
- $V_{s30}$: Average Shea Wave Velocity
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EXECUTIVE SUMMARY

In November 2008, the closure of the East Rand Proprietary Mines (ERPM) resulted in the closure of the last pumping station in the Central Rand Basin, which previously maintained the underground water level. The consequent large scale rise in the water level was and still is responsible for increased levels of seismicity in the area.

The first measurements of the water levels in various compartments of the Central Rand Basin mines started in late 2009. At that time, the water level was the same in all compartments, 900 m below the reference level. The first stations of the Central Rand Basin strong ground motion network installed and operated by the CGS were commissioned in March 2010. Therefore, the observed seismicity over this period is associated with a systematic rise in the water level across all compartments at the same rate. The difference in the level of seismicity cannot be attributed to different water level gradients across different compartments after March 2010.

Monitoring of seismicity in the Central Rand Basin has been an on-going process for over five years. A fundamental question is: how does fluid-induced seismicity in the Central Rand Basin change over time? The level of seismicity in the Central Rand Basin is not showing signs of decreasing with time since the number of strong events is still as high as it was when monitoring began over five years ago.

The seismicity pattern shows a strong relationship between the presence of the mining void and high levels of seismicity. The seismicity did not appear to migrate to areas outside of the old mining boundaries. The following patterns emerged:

- The distribution of seismicity shows that the eastern part of the CRB is still the most active region.
- The northern parts of the ERPM mine and the Rose Deep Germiston mine were active during 2013 and 2014 but near the end of 2014 and beginning of 2015, activity subsided.
New activity arose south of the Durban Roodepoort Deep mine during 2014 and 2015. The area is associated with active mining at the Doornkop and Cooke mines. Also, according to national news headlines, illegal mining operations that can reach depths of up to 1000 m are taking place at the South Roodepoort and DRD mines.

The areas, which include Crown Mines, Robinson Deep and City Deep mines, are active throughout the five year and there is no evidence to suggest that the level of seismicity is decreasing.

Over the last three years a cluster of seismicity has developed, which extends to the south of Crown Mines and Robinson Deep mine. The cluster is located outside of the area delineated by mine boundaries. The cluster of about 20 events could be associated with superficial activities, however, the scattering of the seismic event locations does not allow for the association of the seismicity with a specific type of activity, although, a large quarry is located within the cluster.

Characterization of the seismicity triggered by a rising water level in the Central Rand Basin is achieved through the estimation of source parameters. The spatial and time variation of seismicity in the Central Rand Basin area was analyzed. Special attention was given to seismic source parameters such as magnitude, scalar seismic moment, radiated seismic energy and static stress drop. The relations between source parameters provide an understanding of the physical phenomena that occur in the medium as a result of flooding.

Static stress drop heavily influences ground motion characteristics, which, in urban areas, affects the risk assessment. The amplitudes of ground motion are controlled by the amount of static stress drop during a seismic event; therefore, areas where large stress drop is observed are areas where strong ground motion is expected. The observed static stress drop varied from 0.05MPa to 10MPa. Large static stress drop is not only associated with large events. It was found, that large stress drops were sometimes associated with small as well as large events. The static stress drop...
increases with an increase in the seismic moment for seismic moment values ranging from $10^{10}$ Nm to $10^{13}$ Nm. However, for a seismic moment larger than $10^{13}$ Nm, an upper limit for the static stress drop at 10MPa was found. The radiated seismic energy covers a range of approximately six orders of magnitude while scalar seismic moment varies by four orders. Several comparisons were presented between the seismic source parameters obtained in this study and those of other regions. The dependence between seismic moment and radiated energy in different studies shows a similar pattern to the one observed here. However, there are some significant differences; static stress drop for the Central Rand Basin area is one order of magnitude larger than in the case of observed seismicity induced by a water reservoir in China.

Four events were identified for moment tensor inversion. Three of the four events display oblique strike-slip source mechanisms with the azimuth of the T axis in the North-East and the P axis in the North-West. One of the four events shows also strike-slip mechanism, but the azimuth of the T axis is in the North-West and that of the P axis is in the North-East. The nodal planes as shown by the fault plane solutions are, in general, consistent with the observed fault structures that were observed in the now defunct mines of the Central Rand Goldfields.

A relationship between local and moment magnitude, $M_L$ and $M_w$, was derived. This relationship has important practical applications considering that magnitude provided by the CGS bulletin is $M_L$, while the mining networks use $M_w$.

The magnitude of completeness was established as $M_w = 1.3$ for the catalogue.

A study of the temporal variation of the spectral parameters in the Central Rand Basin showed that the scalar seismic moment was dominated by two earthquakes with values larger than $M_{0Sv} = 10^{14}$ Nm and magnitudes larger than 3. A mean background rate of 1.02 events per day was calculated. The average rate of seismic deformation was $1.6 \times 10^{13}$ Nm/year. This is equivalent to one $M_w 2.7$ event per year. The release
of seismic deformation was not uniform. There are periods of low seismic activity where sections of the cumulative seismic moment curves are approximately \(0.06 \times 10^{13}\) Nm/year. A detailed analysis of the cumulative seismic moment revealed that initially, the eastern part of the area was responsible for the largest portion of the total seismic deformation but on 18 November 2013 the biggest event appearing in the catalogue, occurred in the western part. This implies that the dynamic forces that control seismicity in the area are fluctuating. Over the last five years, the total cumulative seismic moment released in the Central Rand Basin was \(9.0 \times 10^{14}\) Nm. This is equivalent to a single earthquake of magnitude \(M_w\) 3.9, which is significantly less than the largest earthquake experienced during mining times. The largest events to be observed in the Central Rand Basin region occurred in 1974 (\(M_L\) 4.9) and 1980 (\(M_L\) 4.8).

The temporal evolution of the event inter-event time provides an understudying of the physical mechanisms of earthquake interaction. A change in the characteristics of the inter-event time results when a stress change is applied to a group of faults in a region that have been undergoing a constant rate of loading. Results from this study indicate that the fluid-induced behavior of the inter-event time corresponds to a clustering of events. Fluid-induced events do not appear at random, since the density distribution does not follow an exponential distribution function. The actual mechanism of fluid induced seismicity is not well understood. Most scientists are of the opinion that the seismicity is triggered by an increase in pore pressure in the rock mass, which reduces the frictional force on a fault.

Another activity within this project was to model the structural trends within the Central Rand Basin using an assumed pre-mining stress model in order to identify zones in the basin that are more “seismicity-prone” than others. The mechanism for triggering instability in the model is an applied pore pressure, representing the flooding that has taken place. A detailed map of the structural geology together with a review of the structural setting formed the basis for this study. The 12 station seismograph network which spans the Central Rand Basin provided locations of
seismic events with which to validate the results of our model. Results from the 3D models showed an average shear displacement of approximately 5 cm and a maximum 12 cm. Joint shear stresses up to 60MPa were induced by the removal of material to form the void. The model produced stress and strain conditions comparable to those observed underground and demonstrated the strong dependence of an intersecting feature’s propensity to slip on its relative orientation with respect to the mine void. There was good agreement between the spatial distribution of seismicity and the positions of potentially unstable features, which suggests two possibilities: (1) Seismicity is being controlled by stresses induced by the shape and orientation of the mined-out reef on intersecting geology rather than tectonic stresses and (2) The shallow crust can be described by a homogenous material and uniform stress model.

In efforts to understand and mitigate the effects of earthquakes, it is necessary to estimate the magnitude of the largest earthquake that is thought possible within a specified area. The aim of this investigation was to estimate such $M_{\text{max}}$ value for the Central Rand Basin using indirect methods that utilize seismicity data collected from the database of earthquakes in the Council for Geoscience. Methods based on statistics of the collected seismic data previously developed and used widely for $M_{\text{max}}$ estimation were used. The non-parametric (with Gaussian Kernek) procedure for $M_{\text{max}}$ estimation was found to fit observed data best. A value of $M_{\text{max}} = 5.13$ was then estimated. It is clear from obtained results that the estimated value is closely linked to the observed maximum magnitude. Therefore, an effort was also made to use identified faults and their lengths to estimate an independent $M_{\text{max}}$ value. Using the longest fault in the mines of 11.8 km and relations derived by Wells & Coppersmith, a magnitude value of 5.9 was obtained giving the most conservative $M_{\text{max}}$ value. However, geological information on faults in the mining region is not well known and thus investigation to better identify and characterise the faults should continue.

The ground motion prediction is central to mitigating the seismic risk. For that reason, theoretical ground motion spectra for a group of earthquakes located within the
Central Rand Basin were calculated to validate the parametric ground motion model. The parametric ground motion model was controlled by seismic source spectral parameters and attenuation parameters that were estimated from observed seismograms. The model was successfully tested against events with magnitudes ranging from 2.0 to 3.4 and found to be agreeable. Finally, theoretical ground acceleration spectra for possible large earthquakes (magnitudes $M_w$ 4, 5 and 6), that have not yet been observed, were presented. The prediction of ground motion for unobserved earthquakes is a complex process, which required validation using several tests. Therefore, the results presented here should be considered as a first step towards ground motion prediction for the largest expected earthquake.

Probabilistic seismic hazard analysis was performed for areas surrounding the mining regions of the East Rand, Central Rand and West Rand. Hazard maps were produced for Spectral Acceleration (SA) at $T = 0.1s$ and $T = 1.0s$, both at return periods of 475 years and 979 years. The uniform hazard spectra, UHS, for three sites, Central Johannesburg, OR Tambo International Airport and Soweto were prepared. The acceleration values are almost the same at OR Tambo and Johannesburg, whilst values at Soweto are much less.

The expected damage to urban structures typically found in the Johannesburg CBD, due to seismicity, was calculated. Each of the 12 maps represents the 5% probability of exceedance within periods of 5, 10, 15 and 25 years of the expected damage for three specified building classes in the Johannesburg CBD. Based on these assessments, the Johannesburg CBD, Germiston and Bedfordview are three suburbs with the highest exposure to seismic hazard and risk. Low rise buildings with unreinforced masonry, load-bearing walls are the most susceptible to damage with expected damage ranging from 5% to 7%. Damage assessment methodology does not include the effect of amplification of the seismic signal due to characteristics of the near surface geology. The estimated expected damages are small when compared to the damage experience in more seismic active areas or what was observed in countries with devastating earthquakes such as Haiti (12 January 2010) and Nepal.
(25 April 2015). However, it is important to note since South Africa do not have a database of observed damages due to seismic events, the damage estimates provided in this report are based on international vulnerability curves. The results are therefore only a best estimate.

Damage estimates for houses developed under the governmental Reconstruction and Development Program (RDP) are currently not included in this assessment. The damage estimates for areas such as Soweto and Roodepoort may therefore be significantly higher/lower than reported here. During the recent seismic event Mw 5.5 on 5 August 2014 in Orkney, severe damage was observed to many of RDP houses. Current investigations are underway to build an appropriate damage curve for these infrastructures.

A site response analysis was conducted at nine seismograph station locations to investigate this effect. The results for each site are presented in the form of variation of PGA with depth, transfer function, amplification factors and response spectra at ground surface. The characteristics and shape of close and distant ground motion are discussed and it is observed that it has profound effect on site response and amplification factors. The average amplification factors at all sites varied between 1.5 and 3.3. There were a few instances in the analyses, where amplification factors reached values above 10. The lower velocity values, weak and soft material at depths are responsible for the higher amplifications at some sites. The study region consists of thin to thick sedimentary layers overlain on bedrock at some instances and rock outcrop is also available at some locations. The sedimentary layers are undulating in the region and hence, the amplification of seismic waves is very site specific. The local geology and the lower velocity layers entrapped between higher velocity plays a major in estimating the response of ground to the seismic waves.

Please note that the amplification factors vary with the period. The amplification at specific periods affects the structures at different periods. The response of the structure is dependent on the period of the structure also. In a worst scenario when
maximum amplification of seismic waves coincides with the building’s natural period, maximum damage can be expected for the building. From this study, it can be concluded that the predominant period of ground, amplification factors with respect to period and building class would be essential inputs for earthquake risk reduction. It has also been attempted to estimate the crustal amplifications. The crustal amplifications are found to be very low as compared to the amplification in the shallow depths.

**Recommendation:**

1. Temporal and spatial changes in the rock mass of the Central Rand Basin imposed by fluid related seismicity should be evaluated continuously for the next few years. Characterization of the dynamic processes in the rock mass is mainly obtained through estimating the values of the spectral parameters of the seismic source. The techniques used for trend analysis should be further developed to identify small deviations from the long term trend.

2. Analysis of the inter event time revealed that the seismicity occurs in clusters. This is a significant finding because it indicates that the Central Rand Basin experiences times of increased and decreased seismicity, periodically. This phenomenon should be investigated in detail as it has practical implications for a hazard assessment.

3. The prediction of ground motion caused by a maximum expected magnitude, which has not yet been observed, is a complex process, which requires validation using several tests. Therefore, testing of the parametric ground motion model should continue.

4. Attenuation and amplification of high frequency signals caused by near surface geology strongly influences the values of seismic source spectral parameters. Parameters, which control high frequency attenuation, i.e. kappa, must be estimated for all seismic stations to improve the estimations of seismic source parameters.
5. The damage curve for the Central Rand Basin should be recalculated to include data obtained from the Microzonation project sponsored by the Department of Mineral Resources. This project will produce a hazard map with site effects.

6. The strongest and potentially, most damaging ground motions, are observed at closest distances. Therefore, a detailed and systematic analysis of ground motion characteristics, when the seismic source is located close to the seismograph station, is required.
PROJECT INTRODUCTION

6.1 Project Aims

The proposed project addresses the problem of the risks posed by fluid-induced seismicity in the greater Johannesburg area by focusing on accurate quantification of the most important factors that contribute to the estimation of this hazard and risk.

Objective 1: Strong ground motion prediction for the maximum expected magnitude and the evaluation of damage potential, as it is defined by the South African Building Codes.

It is required to develop and implement a realistic assessment of the seismic hazard and risk rooted in well-established methodology developed for tectonic earthquakes. However, it has to be modified in order to accommodate rapid changes in the stress conditions caused by the flood water. The investigation will concentrate on the understanding of seismic source properties, propagation mechanisms and local site effects as the physical factors controlling strong ground motion.

Output 1: Severity of potential damage will be evaluated using response spectra technology with the guidance and requirements of the “Seismic actions and general requirements for buildings”, issued by the South African National Standards.

Objective 2: Development of an Early Warning System for risk reduction by monitoring the state of dynamic processes in the rock mass of the Central Basin.

Changes in the rock mass of the Central Rand Basin imposed by fluid related seismicity should be revaluated periodically. The Central Rand Basin will be divided into cells. In each cell, the value of the parameters that characterize the dynamic processes that currently occur in the rock mass will be displayed. The proposed list of parameters includes: number of events, cumulative deformation, cumulative radiated seismic energy, the largest stress drop. The relationship between apparent stresses and seismic moments will be updated and analysed periodically as well.

Output 2: Maps will be issued presenting changes in states of dynamic processes and trend analysis.

The observed seismicity pattern will establish the relationships between the mining void and geological features in the Central Rand Basin. Trend analysis will be applied
to the time series to measure differences in observed parameters over time. This analysis will be used as an early warning indicator of potential problems.

6.2 Project Hypothesis

In 2009, the South African National Seismograph Network (SANSN), operated by the Council for Geoscience (CGS), observed a dramatic increase in seismicity coinciding with the closure of the pumping stations in the East Rand Proprietary Mines (ERPM) mine. The water flooding the mine void creates a significant and costly environmental impact as large voids are interconnected and are located close to major urban centres in Johannesburg. Based on a theoretical analysis, the magnitude of flooding-induced seismic events that can occur is expected to fall within the range of magnitudes previously observed during mining. The largest earthquakes associated with mining; a magnitude 5.3 earthquake located in Stilfontein in 2005 and more recently, a magnitude 5.5 located near Orkney in 2014, caused serious structural damage. If such an earthquake were to occur in the densely populated urban area of Johannesburg, it could present major safety risks to properties on the surface in the vicinity of the old mines. The occurrence of a flooding-induced event of a similar magnitude cannot be excluded, therefore, should be included as one of the possible scenarios of the strong ground motion prediction. The nature of seismic events triggered by mine flooding, as well as the damage potential of surface ground motions associated with such events, needs to be monitored and investigated.

6.3 Project Methodology

The tasks were spread over period of three years. This report is focused on milestones delivered during the third and final year, for which the starting points were results obtained during the first two years of the project. For completeness, the descriptions of the tasks are followed by titles of the contributing milestones and the years in which the milestones were completed.
To improve the monitoring capacity around the Central Basin, the Seismological Unit of the CGS installed and has operated a dense seismic network since the first quarter of 2010. The dense network consists of 12 strong ground motion seismic sensors. The SANSN locates seismic events with an uncertainty of 5km in contrast to the dense network, which has a location uncertainty of less than 1km. This high accuracy enables meaningful interpretation of the seismicity pattern. Whilst the monitoring of seismicity associated with the flooding of the Central Basin cannot prevent the events from occurring, it is important to continue with this activity using the CGS infrastructure already in place. Continued monitoring and its interpretation will track the observed changes in the seismicity and provide insight into the risk posed by these events. Investigations will utilize strong-motion recordings obtained from the 12 station network and water level measurements from mine voids. The two major activities are proposed to directly address the hazard and risk posed by the seismicity related to flooding voids in Central Basin. The static stress drop at a seismic source, which characterizes specific types of seismic events, will be determined for these fluid induced events and is crucial to predicting future, larger ground motions. The nature of seismic events triggered by mine flooding, as well as the damage potential of surface ground motions associated with such events, needs to be monitored and investigated.

**Objective 1**

This objective is to predict ground motion caused by the largest possible seismic event. The largest earthquake observed recently in the Central Rand Basin had a magnitude of 3.6. However, it is expected that the maximal earthquake magnitude could be as high as 5.3 or 5.5. To predict ground motion caused by such a large magnitude, a model for the ground motion prediction has to be constructed. Ground motion is controlled by three components: seismic source, attenuation of the seismic wave along the ray path and possibly by amplification caused by near surface geology.

**Task 1. Ground Motion Prediction and Response Spectra.** Severity of potential damage should be evaluated in respect to South African regulations. Earthquake engineering research for over decades has resulted in the development of designs and detailed methodologies, which ensure that structures can safely withstand severe
ground shaking without sustaining excessive damage and human casualties. Several standards for the design and safety requirements of urban structures exist.

(1) The evaluation of ground motion for this project will follow guidelines and requirements of the South African National Standards, (Basis of structural design and actions for buildings and industrial structures, Part 4: Seismic actions and general requirements for buildings). Ground motion can be specified in many different ways, i.e. peak ground acceleration, shapes of response spectra and time history. The building design requirements generally use response spectra and/or time history to represent ground motions.

This task is addressed in Milestone 3: “Ground motion prediction and experimental response spectra” (year 1) and Milestone 2: “Stochastic 1D seismic site response analysis” (year 3).

(2) Development of methodology to calculate the magnitude of the maximum possible seismic event. Two factors will be considered: one is based on the assumption that the currently observed increase in seismicity is caused by changes in the ground water level. Secondly, it is assumed that flooding water is capable of triggering a tectonic earthquake.

This task is addressed in Milestone 4: “Expected maximum magnitude estimation” (year 1)

(3) Probabilistic seismic hazard assessments (PSHA), which involve the construction of a regional seismotectonic model on the basis of the earthquake catalogue and geological information regarding the tectonic structures of the area. The construction of a logic tree will consider and weight all possible alternative models in order to incorporate all uncertainties.

This task is addressed in Milestone 2: “Probabilistic seismic hazard analysis for hard rock” (year 2).

(4) The expected damages for 12 of the most characteristic building classes in the Johannesburg CBD will be estimated. The purpose of the project is the quantification of the expected damage to urban structures typically found in the Johannesburg CBD, due to the seismicity generated by an increase in the water level in abandoned mines.
This task is addressed in Milestone 4: “Risk assessment for different types of structures”, (year 2), and Milestone 5: “Assessment of expected damage to most representative buildings in the Johannesburg CBD”, (year 3).

(5) Validation and verification of ground motion has be performed using real data in order obtain uncertainties in the model. This is crucial since earthquakes of a maximal observed magnitude will be used to predict the ground motion of larger, future earthquakes.

This task is addressed in Milestone 3: “Validation of the Parametric Ground Motion Model Derived for the Central Rand Basin Mines”, (year 3).

Task 2. Attenuation. The evaluation of the attenuation of ground motion amplitude is an essential part of the seismological characterization of a region. The path effect is given by the multiplication of the geometrical spreading and the diminution function represents the attenuation of seismic waves passing through the earths crust. The attenuation of seismic waves in the KOSH and Far West Rand mining districts has already been estimated (Cichowicz and Birch, 2010).

(1) In the first year of the project those results will be used as an approximation to the attenuation in the Central Basin, however, to obtain a better ground motion prediction, in the second year of the project, the attenuation for the Central Rand Basin must be determined.

This task is addressed in Milestone 1: “Attenuation of seismic waves in the CRB area”, (year 2), and Milestone 3: “Validation of the Parametric Ground Motion Model Derived for the Central Rand Basin Mines", (year 3).

Task 3. Site Effect. A significant part of the damage related to destructive earthquakes around the world is associated with seismic wave amplification due to local site effects. The local site conditions could be very different due to variations in thickness and properties of soil layers, and could have significant effects on the characteristics of earthquake ground motions on the ground surface. Much effort should go into accounting for the modifications of the ground motion due to local site geology.

(1) Site effects will be modeled using the full soil profile obtained from three pilot sites located in the Johannesburg area near old mines. Field reconnaissance will be undertaken for visual assessment and evaluation of any potential geological/geotechnical constraints visible on the surface. All available borehole
information from drilling programs will be assessed and various models will be created. The depth and thickness of the soil cover will be estimated.

This task is addressed in Milestone 5: “Measurement of soil properties at sites, where maximum ground motion amplification is expected”, (year 1), and Milestone 3: “Subsurface engineering evaluation of the Johannesburg City area”, (year 2).

(2) This will be used as the basis for the drilling program and geotechnical surveys. At least six 165mm diameter boreholes will be drilled using a down-the-hole. Chip samples will be retrieved, inspected and logged according to current practice. A report will include an assessment of the depth to bedrock in the proposed study areas.

This task is addressed in Milestone 5: “Measurement of soil properties at sites, where maximum ground motion amplification is expected”, (year 1).

(3) The site classifications used in earthquake regulations have been based on the use of the shear wave velocity vertical profile. Therefore, field work will be conducted to measure the shear wave velocity profile using the Multichannel Analysis of Surface Waves method, and fundamental frequency of the soil using the spectral ratio method.

This task is addressed in Milestone 4: “Shallow crustal structure in the Central Rand Basin using local earthquakes and multi-channel analysis of surface waves method”, (year 3).

(4) Once the geotechnical characteristics of a site are known, then the dynamic response of the soil to strong ground motion will be estimated using numerical analysis. The one dimensional soil response is the main method used in earthquake engineering practice.

This task is addressed in Milestone 2: “Stochastic 1D seismic site response analysis”, (year 3).

Objective 2

Earlier studies of the effects of water load on reservoirs concluded that reservoir-induced seismicity is controlled by the pre-existing stress regime, hydro-geologic properties of the region, spatial characteristics of the reservoir, complex interaction between the elastic stresses, pore pressure from elastic and diffusion mechanisms and fault lubrication. The temporal distribution of induced seismicity following the
filling of reservoirs shows two types of response: (a) Rapid response, in which the seismicity follows immediately on first loading of the reservoir. It consists primarily of low magnitude swarm-like activity and is confined to the immediate reservoir area. It is also closely correlated with changes in water level within the reservoir. (b) Delayed response, in which the seismicity follows after a significant delay from the first filling. It is often associated with large magnitude earthquakes and may extend significantly beyond the confines of the reservoir. The driving force of the delayed response is mostly fault lubrication. It may also not show an immediate correlation with major changes in the reservoir level. Both responses are possible in the Central Basin reservoir. There are substantial differences in the temporal and spatial characteristics of the response of the rock mass to these processes and it should be possible to identify the dominant mechanism through a correlation between the changes in seismicity and water level in the reservoir. Most seismicity in the Central Basin is controlled by water ingress which will be stabilized most likely in 2013. International experience with water induced seismicity shows that seismicity will be reduced a few years after the water level is stabilized. Therefore, seismic monitoring has to be conducted for a period of about 5 years after the water level and static stress in the rock mass are stabilized. The stress regime will be changed with time so accurate evaluation of risk and hazard parameters has to be repeated periodically.

Task 1. Preliminary data analysis of waveforms. Strong-motion recordings obtained from the network of 12 strong ground motion stations will provide data.

(1) This step includes re-picking the P and S wave arrival times, the location of seismic events (longitude and latitude) using a local velocity model and local magnitude.

This task is addressed in Milestone 2: “Estimation of seismic source parameters”, (year 1), Milestone 5: “Temporal and spatial variation of seismicity in 2012/2013”, (year 2), Milestone 6: “Velocity models and spatial variation of seismicity in the Central Rand Basin”, (year 3) and Milestone 7: “Spectral parameters of the seismic sources and their temporal variation in the Central Rand Basin”, (year 3).

Task 2. Estimation of seismic source parameters.

(1) Each well recorded seismic event will be characterized by scalar seismic moment, $M_w$ magnitude, radiated seismic energy, source size, static stress drop and apparent stress drop. Estimation of source parameters becomes more and more reliable as the model for the attenuation of seismic waves gradually improves as a result of activities under Objective 1.
This task is addressed in Milestone 2: “Estimation of seismic source parameters” (year 1), Milestone 5: “Temporal and spatial variation of seismicity in 2012/2013”, (year 2), Milestone 6: “Velocity models and spatial variation of seismicity in the Central Rand Basin”, (year 3), Milestone 7: “Spectral parameters of the seismic sources and their temporal variation in the Central Rand Basin”, (year 3), and Milestone 3: “Validation of the Parametric Ground Motion Model Derived for the Central Rand Basin Mines”, (year 3).

(2) The focal mechanisms of events with $M_w$ 3.0 or larger will also be calculated.

This task is addressed in Milestone 7: “Spectral parameters of the seismic sources and their temporal variation in the Central Rand Basin”, (year 3).

(3) Additionally, site effects have to be estimated at the 12 strong ground motion stations.

This task is addressed in Milestone 2: “Stochastic 1D seismic site response analysis” (year 3).

(4) In the second and third year of the project, once the path and site effects are estimated, the evaluation of a fluid related seismic source will be studied to reveal the physics of the seismic source. Developing a suitable model for the seismic source that can be used to characterize the flood induced seismicity is the most critical part of project. Special attention will be given to comparing stress drops of events related to fluid with events related to mining.

This task is addressed in Milestone 5: “Temporal and spatial variation of seismicity in 2012/2013”, (year 2), Milestone 6: “Velocity models and spatial variation of seismicity in the Central Rand Basin”, (year 3), and Milestone 7: “Spectral parameters of the seismic sources and their temporal variation in the Central Rand Basin”, (year 3).

**Task 3. Spatial variation of seismicity.** The region under study was divided into 2 km x 2 km cells and in the second stage, the size of the cells will be controlled by the geology of the region. The Central Basin geology is dominated by quartzite/conglomerates of Witwatersarand, Supergroup, volcanic rocks of Ventersdorp Supergroup and Precambrian granites. The observed seismicity will be analyzed to reveal both spatial clustering and scattering across a large area. Analyses will look for all possible seismicity patterns: temporal clustering followed by long periods of quiescence and migration of seismicity from one area to another.

(1) Every six months five maps will be released and distributed to users. They will show plan view of the Central Basin divided into cells. Each cell will display the following parameters: (a) number of earthquakes, (b) cumulative deformation caused
by earthquakes, (c) cumulative radiated seismic energy (d) the largest stress drops
associated with seismic events, (e) the largest apparent stress drops. An observed
seismicity pattern will establish relationships between the mining void and geological
features. Maps will show the geology, mine contours and the city of Johannesburg
and they will be distributed to the users every 6 months.

This task is addressed in Milestone 6: “Spatial variation of seismicity in the Central
Rand Basin, in 2011”, (year 1), Milestone 5: “Temporal and spatial variation of
seismicity in 2012/2013” (year 2) and Milestone 6: “Velocity models and spatial
variation of seismicity in the Central Rand Basin”, (year 3).

Task 4. Temporal variation of seismicity and trend analysis. (1) Time series of the
following parameters will be produced: (a) seismicity rates, (b) cumulative
deformation caused by earthquakes, (c) cumulative radiated seismic energy (d) stress
drop associated with the largest seismic event, (e) apparent stress drop for largest
seismic events and (f) cumulative number of events for different magnitude
thresholds. (2) Trend analysis over long periods allows for the measuring of
differences in seismic source parameters over time. Trend analysis between source
parameters will attempt to spot a pattern, which will reveal any jump or decline in the
relationships. Graphs of trends and interpretations will be periodically distributed to
users every 6 months. (3) Additionally, a list of observed maximal parameters of
ground motion will be provided. (4) Relations between source parameters such as
stress drop versus seismic moment, seismic energy versus seismic moment and
others will be provided every 6 months. These relationships will help in understanding
the physical phenomena that occur in the medium due to void flooding.

This task is addressed in Milestone 5: “Temporal and spatial variation of seismicity in
2012/2013”, (year 2), and Milestone 7: “Spectral parameters of the seismic sources
and their temporal variation in the Central Rand Basin”, (year 3).

Task 5. Change in uniform hydraulic pressure. (1) On a regional scale, looking at
the change in hydraulic pressure due to the rising of mine water over the Central
Basin based on the assumption that the hydraulic pressure uniformly acts on the
underground mine voids.

This task is addressed in, Milestone 7: “Modeling of changes in hydraulic pressure in
the Central Rand Basin”, (year 1).

Task 6. Change in anisotropic hydraulic pressure. (1) Looking at the change in
hydraulic pressure that is acting on the underground structure which may lead to the
uneven distribution of crustal stress that directly impacts on the occurrence of
earthquakes, especially in the eastern portion of the Central Basin. This research will be conducted on the basis of underground mine data and the mine water monitoring data. While targeting the problem of localized and anisotropic hydraulic pressure, which has the potential of impacting on the occurrence of seismic events in the Central Rand Basin, detailed mine planes with the distribution of mine voids will be collected and analysed. Data of underground linear structures such as faults and dykes will also be collected and collated. In addition, in order to simulate the anisotropy of hydraulic pressure due to a change in the mine water level, modelling software based on the finite element approach is required.

This task is addressed in Milestone 6: “Stress modeling in mining areas – defining zones of seismic potential”, (year 2).

### 6.4 Project Milestones

<table>
<thead>
<tr>
<th>NO.</th>
<th>MILESTONE Year 3 (this report)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project initiation</td>
</tr>
<tr>
<td>2</td>
<td>Stochastic 1D seismic site response analysis</td>
</tr>
<tr>
<td>3</td>
<td>Validation of the Parametric Ground Motion Model Derived for the Central Rand Basin Mines</td>
</tr>
<tr>
<td>4</td>
<td>Shallow crustal structure in the Central Rand Basin using local earthquakes and Multichannel Analysis of Surface Waves method</td>
</tr>
<tr>
<td>5</td>
<td>Assessment of Expected Damage to Most Representative Buildings in the Johannesburg CBD</td>
</tr>
<tr>
<td>6</td>
<td>Velocity models and spatial variation of seismicity in the Central Rand Basin</td>
</tr>
<tr>
<td>7</td>
<td>Spectral parameters of seismic source and its time variation in the Central Rand Basin</td>
</tr>
<tr>
<td>8</td>
<td>Draft final report</td>
</tr>
<tr>
<td>9</td>
<td>Final Report</td>
</tr>
</tbody>
</table>

### 6.5 Champion Mines

Fluid-Induced Seismicity in the Central Basin area occurring in abandoned mines. There are no current owners of these mines.
MILESTONE DELIVERABLES

7.1 MILESTONE 1: Project initiation and Introduction

The project initiation milestone included a presentation of the project proposal at the MHSC offices in Woodmead, Johannesburg. This was successfully completed.

The Central Rand Basin forms the northernmost goldfield of the Witwatersrand Basin. It stretches approximately 50 km from west to east along outcrops of the Main Reef Leader, the Main Reef, and the South Reef, which form the most important gold-bearing ore bodies in this region. Mining extended from the surface down to 3500 m underground along much of the extent of the Central Rand Basin, commencing in 1886 after the discovery of the goldfield and finally ending in 2008 with the closure of East Rand Proprietary Mines (ERPM). In 2008 ERPM was pumping between 40,000 and 60,000 m$^3$/day. This amount of pumping was required to keep the water level at a constant depth. Once ERPM closed, pumping stopped and the water level started to rise. Currently, the water level in the mining voids of the Central Rand Basin area is being maintained at approximately 150 m below the surface. The number of earthquakes in the Central Rand Basin area increased after water ingress into the mining voids caused the underground water levels to rise.

The effect of a rising water level on seismicity would best be investigated in a mined-out area of the Central Rand Basin where, for a suitable time period, no mining has taken place. Mining operations ceased across most of the Central Rand Basin in the late 1950 with only DRD (in operation up to 2001) and ERPM (operational up to November 2008) remaining active. Figure 1(top) shows seismicity recorded by the South African National Seismograph Network (SANSN) in the Central Rand Basin excluding the ERPM and DRD mines for an 11 year period from 1 January 2004 to 30 December 2014. In most cases, the location of events was constrained by three or four stations resulting in a low accuracy of location and possible error of up to 10 km. Figure 1(middle) shows changes in the water level below the Gold Reef City No 14
shaft collar for the same period (Dr Lin and Mr. De Meillon, personal communication). Figure 1 (bottom) shows the gradient of the water level. The gradient was plotted by interpolating row data using the spline method, applying smoothing and using a step of 30 days to obtain the gradient.

Between 2004 and the end of 2008, the water level at ERPM was stable at a depth of roughly 3,000 m below the surface. Across the rest of the Central Rand Basin, the water level varied between 650 m (DRD) and 1100 m (SJ Howard shaft) below surface. A dramatic rise in the water level was observed in 2009, which is associated with a significant increase in the number of events. The gradient, i.e. change in water level, spiked sharply in 2009, peaking in 2010. From 2010 to 2015 a gradual shift back towards a zero gradient took place as the change in water level slowed. The water level has stabilized at 150 m below surface with the recommencement of pumping in 2014 at a rate of 40,000 m$^3$/day.

The rate of seismicity presented in Figure 1 is seen as an indicator of the relationship between seismicity and the water level in the mining voids. However, the detailed analysis of seismicity patterns and seismic source parameters presented here, was based on data obtained from the dense, 17-station strong ground motion seismograph network. In early 2010, the South African National Seismograph Network was expanded with the intention to estimate the direct influence of shutting down the pumping stations on seismic activity in the Central Rand Basin.
Figure 1: (Top) Bars with the number of events per 30 days for a period of 11 years from 1 January 2004 to 30 December 2014. The events were located in the Central Rand Basin, excluding the ERPM and DRD mines. (Middle) The water level below the Gold Reef City No 14 shaft collar. (Bottom) Gradient of the water level below the Gold Reef City No 14 shaft.
7.2 **MILESTONE 2: Stochastic 1D seismic site response analysis**

Local site conditions and particularly shallow depth soil properties play an important role in earthquake-resistant design and must be accounted for on a case-by-case basis. The aim of this part of study is to predict the amplification of seismic waves for various sites in Johannesburg by considering the parametric and ground motion uncertainty. The location map of all sites considered in the study is given in Figure 2. The estimated site classes as per National Earthquake Hazard Reduction Programme, NEHRP (BSSC, 2001) for these nine sites are given in Table 1. All of the sites fall under site class B and C as per NEHRP site classification. The location MASW09 (ENOC) is just on the boundary of NEHRP site class C and D. The lower velocity values suggest loose soils overlain on the bedrock. This site coincides with the graben, i.e. sediment with low velocity. The NEHRP site classification is given in Table 2. The local site conditions could be very different due to variations in thickness and properties of soil layers and could have significant effects on the characteristics of earthquake ground motions on the ground surface. The soil amplification factors are directly related to the shear-wave velocity profiles, modulus degradation and damping ratio of the soil. Site response analysis is therefore a fundamental part of assessing the amplification of shallow depths.

![Figure 2: Location map of sites considered in the study](image-url)
Table 1 Average Shear Wave Velocities ($V_{S30}$) of the sites

<table>
<thead>
<tr>
<th>MASW Point</th>
<th>Station Code</th>
<th>$V_{S30}$</th>
<th>NEHRP Site Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASW01</td>
<td>BNON</td>
<td>684.733</td>
<td>C</td>
</tr>
<tr>
<td>MASW02</td>
<td>GOUD</td>
<td>1048.105</td>
<td>B</td>
</tr>
<tr>
<td>MASW03</td>
<td>KFND</td>
<td>1055.009</td>
<td>B</td>
</tr>
<tr>
<td>MASW04</td>
<td>CNVL</td>
<td>1041.760</td>
<td>B</td>
</tr>
<tr>
<td>MASW05</td>
<td>UNJO</td>
<td>1076.426</td>
<td>B</td>
</tr>
<tr>
<td>MASW06</td>
<td>OBSV</td>
<td>707.066</td>
<td>C</td>
</tr>
<tr>
<td>MASW07</td>
<td>SPCM</td>
<td>533.233</td>
<td>C</td>
</tr>
<tr>
<td>MASW08</td>
<td>WALT</td>
<td>895.712</td>
<td>B</td>
</tr>
<tr>
<td>MASW09</td>
<td>ENOC</td>
<td>383.221</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 2 NEHRP Site Classes based on $V_{S30}$ (BSSC, 2001)

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Soil Profile</th>
<th>$V_{S30}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>A</td>
<td>Hard Rock</td>
<td>&gt;1500</td>
</tr>
<tr>
<td>B</td>
<td>Rock</td>
<td>&gt;760</td>
</tr>
<tr>
<td>C</td>
<td>Very dense soil and soft rock</td>
<td>&gt;360</td>
</tr>
<tr>
<td>D</td>
<td>Stiff soil</td>
<td>180</td>
</tr>
<tr>
<td>E</td>
<td>Soft soil</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Peat / highly organic clays</td>
<td></td>
</tr>
</tbody>
</table>

There are various sources of uncertainties involved in the site response analysis. The uncertainties in specification of the input rock motions, characterization of the shear wave velocity profile ($V_S$) and characterization of the nonlinear soil properties are
modelled in the present work. The use of deterministic site response analyses is inadequate and hence, complex and computationally expensive stochastic 1D seismic response analyses is attempted here which allows taking into account the uncertainties involved.

The present method involve modeling uncertainty in shear wave velocity, soil non-linearity and ground motions. A typical shear wave velocity profile with realization within its probability distribution at station KFND is shown in Figure 3. The variation in modulus reduction and damping curve with Seed and Idriss (1970) mean curve for sandy soils as a baseline is shown in Figure 4 at ± 1σ and ± 2σ. The variability in input ground motion (which is very significant) for ground response is adopted by selecting ten recorded motions of selective magnitude and distance range from the deaggregation results. The ground motions are selected for a three magnitude values (M_L = 3.10, 3.30 and 3.62) and distance range of 2.0 to 60.0 km. The input ground motions in terms of acceleration with distance varying from 2.8 to 56.9 km is shown in Figure 5. The acceleration response spectra at 5% damping of the ten selected records are shown in Figure 6. The effect of very small, small and moderate distances can be clearly distinguished in Figure 5. These ground motions are recorded on cluster network maintained and operated by CGS. Usually, the effect of magnitude on the spectral shape of ground motion is more significant than the effect of epicentral distance. So, the records were selected accordingly in shorter magnitude range and broader epicentral distance range. The main seismological characteristics of ground motions selected are given in Table 3.
Figure 3: Typical shear wave profile with realizations at station KFND. The grey lines are realizations, thick line is median profile and dotted lines are ± 1σ.

Figure 4: Randomized nonlinear soil property curve
Figure 5: Input ground motions
**Figure 6**: Acceleration Response Spectra (at 5% damping) of Input Ground Motion Records at Bedrock

**Table 3** Seismological Characteristics of the Ground Motion Records Selected

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Date</th>
<th>Magnitude</th>
<th>Epicentral Distance (km)</th>
<th>Recording Station</th>
<th>Component</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM1</td>
<td>2010/07/16</td>
<td>3.30</td>
<td>2.892</td>
<td>GOUD</td>
<td>East</td>
<td>0.01581</td>
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Each shear wave velocity profile was compared with the borehole data and then used in the analysis. Each profile was excited at bedrock with the 10 selected ground motion time histories simultaneously and the ground motions were allowed to propagate though the profile. The soil non-linearity properties and shear wave velocities were varied within the standard deviation and such nine profiles were modelled in the analysis. Hence, each layer of the profile was analysed 100 times and the median values of output are monitored and captured carefully. The estimated amplification factors and response spectra at surface for site ENOC are shown in Figure 7 and Figure 8 respectively.

Based on the results of the analysis, the sites may sustain amplification in the range of 2 to 4 at zero periods. The average amplification factors at all sites are varying from 1.5 to 3.3. For each site (profile), a detailed analysis consisting of 100 realizations has been carried out. The results are shown with the individual as well as median values. The maximum absolute amplification factors in complete matrix of one analysis are found to vary from 6.0 to 15.0. Details of amplification factors and PGA for all nine sites are given in Table 4.

The absolute maximum amplification factors for UNJO and ENOC sites are found to be very high. These are the highest values calculated in analysis and are at particular period for particular combination of properties and these amplification factors should not be treated as an average amplification occurring at a site. The average amplification factors at UNJO and ENOC are found to be 1.836 and 3.344 respectively. At site UNJO, very low shear wave velocity layers are entrapped between high shear wave velocity layers at a depth of 3.0 to 6.0 m. Hence, the
absolute maximum amplification is higher however, the average amplification factor is found to be 1.836. The site ENOC is coinciding with the graben having sediments of low velocity which resulted in very low average shear wave velocity ($V_{S30}$). This site is just on the boundary of NEHRP site class C and D. The lower velocity values suggest loose soils overlain on the bedrock. The loose soils or sediments with low shear wave velocity can expect a higher amplification. The maximum absolute amplification for ENOC is observed as 15.118 which is at particular period for particular combination of properties and this amplification factor should not be treated as an average amplification. The average amplification factor at ENOC is found to be 3.344.

Figure 7: Amplification factors at site ENOC
Figure 8: Response Spectra at Surface for Site ENOC
Table 4 PGA and Amplification Factors for all Sites

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<th>Amplification Factors (at Median)</th>
<th>Absolute Max Amplification Factor in Analysis</th>
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Note: Absolute maximum amplification is estimated in a matrix of one analysis. These are the highest values calculated in analysis and are at particular period for particular combination of properties. The Absolute maximum amplification should not be treated as an average amplification occurring at a site.
7.2.2 Conclusions from Milestone 2

The results for each site are presented in the form of variation of PGA with depth, transfer function, amplification factors and response spectra at ground surface. Very high variation among the results of each profile has been observed. The uncertainty in ground motion (PGA, magnitude, distance, decaying envelope) are responsible for the high variation in the results and for amplification of the seismic waves in shallow depths. The characteristics and shape of close and distant ground motion are discussed and it is observed that it has profound effect on site response and amplification factors. The lower velocity values, weak and soft material at depths are responsible for the higher amplifications at some sites. The study region consists of thin to thick sedimentary layers overlain on bedrock at some instances and also rock outcrop is also available at some locations. The sedimentary layers are undulating in the region and hence, the amplification of seismic waves is very site specific. The local geology and the lower velocity layers entrapped between higher velocity plays a major in estimating the response of ground to the seismic waves.

Please note that the amplification factors vary with the period. The amplification at specific periods affects the structures at different periods. The response of the structure is dependent on the period of the structure also. Building type/class, material properties, dimension ratios contribute towards the stiffness of the structure and are responsible for damage during earthquake shaking. In a worst scenario when maximum amplification of seismic waves coincides with the building’s natural period (natural period of building is dependent on building class), maximum damage can be expected for the building. From this study, it can be concluded that the predominant period of ground, amplification factors with respect to period and building class would be essential inputs for earthquake risk reduction. It has also been attempted to estimate the crustal amplifications. The crustal amplifications are found to be very low as compared to the amplification in the shallow depths.
Ground motion prediction is central to mitigating the seismic risk in the Central Rand Basin. The aim of this is to, as accurately as possible; predict the ground motion that will result from an earthquake of a given magnitude. Seismic source spectral analyses of seismographic data over a period of more than 2 years have produced ground motion parameters for observed earthquakes of various magnitudes. The source parameters were calculated using different estimations for site and path effects, which together characterize the observed ground motion. Stochastic Model Simulation (SMSIM) software (Ver. 4.1), which is a collection of FORTRAN programs written by David M. Boore to simulate ground motion based the stochastic method, was used to calculate theoretical ground motion spectra.

The method uses parametric functions to represent the physical components of ground motion (source, path, site and instrument). The method is useful in simulating ground motions in areas where large damaging earthquakes have not yet been observed. This study compared observed acceleration spectra with results from simulations of the parametric model.

7.3.1 Results per Milestone 3

The description of the stochastic model identifies parameters that control the source model, path attenuation and site effects. This particular version of a stochastic model is our chosen model for the acceleration spectrum of ground motion in the Central Rand. A comparison with observed spectra was done to demonstrate the applicability of the model. 31 reference events with moment magnitudes varying between $M_W$ 1.98 and $M_W$ 3.37 were grouped into bins of similar $M_W$. Four sets of events with approximate magnitudes of $M_W = 2.05$, $M_W = 2.44$, $M_W = 2.68$ and $M_W = 3.00$ were created.
The stochastic model simulation provides an opportunity to test the parametric model assuming that the rest of the model already includes satisfactory parameters. Using the constant-Q attenuation model, kappa was adjusted in steps of 0.005 from 0.005 to 0.015 for the event Mw 2.68. The value kappa = 0.010, clearly shows a much improved fit (Figure 9) to the geometric mean of the spectra for events of magnitude Mw 2.68 using a constant-Q attenuation of 400.

**Figure 9:** Observed spectra (grey lines) and the geometric mean (red) for events of Mw 2.68 with an average SH stress drop of 30 bar recorded at a distance of 4 km. Results from the simulated ground acceleration spectrum using the kappa = 0.005 (green), kappa = 0.010 (purple) and kappa = 0.015 (blue).

The stochastic ground motion model was used to simulate the spectra of large events that have not yet been recorded in the Central Rand Basin, using the relationships derived through the comparisons against observed spectra. Kappa was set at 0.010 while leaving Q-attenuation constant at 400.
Seismicity in the Central Rand Basin is characterized as fluid-induced due to the filling of remnant mine voids through ground water re-charge and openings on the surface. The induced water pressure triggers movement along existing discontinuities that were formed before and during mining. It is unlikely that the events are a result of fresh rock breaks. Global studies of fluid-induced seismicity characterize the static stress drop as low (1 bar) (Hua et al., 2013).

Considering the source parameters presented by Cichowicz in Output 7 of this project as well as the generally low expected static stress drop for fluid-induced seismicity, a value of 100 bar was selected as an input to the simulation for magnitudes Mw 4, 5 and 6 as possible future damaging earthquakes (Figure 10, Figure 11 and Figure 12).

![Figure 10: Expected ground acceleration spectra for a magnitude Mw 4 earthquake.](image)
Figure 11: Expected ground acceleration spectra for a magnitude Mw 5 earthquake.

Figure 12: Expected ground acceleration spectra for a magnitude Mw 6 earthquake.

7.3.2 Conclusions from Milestone 3

Stochastic Model Simulation (SMSIM) software (Ver. 4.1) to simulate ground motion based the stochastic method, was used to calculate theoretical ground motion
spectra. The theoretical spectra were compared with raw observed ground acceleration spectra from earthquakes with similar moment magnitudes and recorded at similar distances. The initial comparisons were performed using approximations for site and path effects. A deviation from the averaged spectra was seen at higher frequencies (> 20 Hz) for close observations (< 15 km). At further distances, the match between simulated and observed improved.

One of the advantages of the stochastic method lies in the ability to test the various parametric functions that represent the physical components of ground motion. The suitability of the path effect function was tested using models derived for the Central Rand Basin and other areas characterized by mining related seismicity. The constant-Q model (Q = 400) was shown to be suitable. The site effect parameter, kappa, was also adjusted and an optimal fit was found where $\kappa = 0.010$.

Finally, the expected ground acceleration spectra for possible large magnitudes not yet observed, $M_w = 4$, $M_w = 5$ and $M_w = 6$, were presented. The calculations were based on the improved parametric ground motion model.

7.4 **MILESTONE 4: Shallow crustal structure in the Central Rand Basin using local earthquakes and Multichannel Analysis of Surface Waves method**

The objective in the first part of this study is to obtain a 1-D velocity models for the upper 5 km crustal structure of the Central Basin using the joint inversion of receiver functions (generated by seismic sources at local distances) and Rayleigh wave dispersions (from ambient noise disturbances). Local earthquakes with the epicentral distance of 0–50 km recorded by the Strategic Water Mine Project (SWMP) seismic network were used to obtain P-wave receiver functions.

The Multichannel Analysis of Surface Waves (MASW) method was employed at 8 seismograph station sites across Johannesburg and one thick soil site. The method
was used to measure the vertical shear wave velocity profile down to between 30 m and 50 m. The profiles are commonly used in geotechnical site classifications and also as a starting model for deeper inversion of the crustal structure.

7.4.1 Results per Milestone 4

7.4.1.1 Shallow crustal structure in the Central Rand Basin using local earthquakes

The advantage of jointly inverting both the receiver functions and surface wave dispersions at each recording station lies in combining the strengths (as indicated above) of both so as to obtain better resolved 1-D depth-velocity profiles of the earth structure beneath the station. The joint inversion method has been successfully applied to investigate the lithospheric structure of continental platforms across the globe. The joint inversion method is basically a linearized inversion approach that minimizes a weighted sum of the L2 norm of the vector residuals corresponding to each of the receiver functions and surface wave dispersions plus a model vector difference norm (Ammon et al., 1990). The weighting among the data sets is composed of normalization constants that are helpful in equalizing the contribution of each data set to the overall misfit of the cost function. Each data set is normalized by the number of data points, variances and an influence factor controlling the relative influence of each data set on the inverted 1-D Vs models (Julià et al., 2000). The model vector difference norm helps in stabilizing the inversion procedure by placing smoothness constraints on the resulting 1-D Vs-depth profiles. A higher smoothness parameter results in smoother Vs-depth profiles but with less resolution whereas a smaller or zero smoothness parameter results in rougher Vs models but with higher resolution (Julià et al., 2000; see Figure 8 in Kgaswane et al., 2012). The model difference norm corresponds to second order differences between adjacent layers (Ammon et al., 1990; Julià et al., 2000). The resulting Vs models are a delicate balance between fitting observations, model simplicity and a priori constraints (Julià et
Rayleigh wave group velocities (periods of 0.5–4 sec) used in this study were produced from ongoing ambient noise studies of the Central Basin (Mangongolo, pers. comm.). Three of the dispersions used for stations ALBD, RDWR and BNON represent localized Rayleigh wave group velocity variations beneath those stations between periods of 0.5 and 4 sec. For the rest of the stations, an average Rayleigh dispersion (obtained from ambient noise studies of the Central Basin) between periods of 0.5 and 4 sec was used in the joint inversion. Both the localized and average Rayleigh wave group velocities were combined with regional Rayleigh group velocities (obtained from a grid point of each station) at periods of 10–105 sec (Raveloson et al., 2012) so as to obtain a regionally representative dispersion that will assist in the constraint of shallow crustal structure. Figure 13 below describes resultant velocity models from the joint inversions. Detailed joint inversion results are shown in Appendix 13.1.
Figure 13: Velocity models obtained from the joint inversions (top diagram). Average Vs profile (together with the uncertainties) based on the velocity curves indicated in A. The inversions involving only the localized dispersions are denoted as station_disp.
7.4.1.2 Multichannel Analysis of Surface Waves method

Data analysis in the MASW method includes the extraction of experimental dispersion curves from surface waves and the running of inversion algorithms to obtain the near-surface shear-wave velocities. To improve the spectral resolution of dispersion images, MASW records were collected using different types of linear spread configurations (see Table 5). A dispersion image for each record was calculated using the phase velocity analysis technique. The dispersion images were then combined to enhance the dispersion curve. Combinations varied according to the available data quality.

The inversion process calculates a shear-wave velocity profile with a proposed theoretical dispersion curve selected by the user that matches the observed dispersion image. The resulting shear-wave velocity profile was then used to produce the theoretical dispersion curve across the full frequency range and at higher modes. This gave an indication of the true match. This iterative process was repeated until the best match was found.

Below is an illustration of the procedure for the soft soil site, ENOC, which shows the plotted dispersion curve in the dispersion image (Figure 14) and the result of the inversion process, which matches the curve to a 10-layer shear-wave velocity profile (Figure 15). The same procedure was followed for all sites and the results are listed in Table 5.
ENOC:

Figure 14: Final combined dispersion image with the fundamental mode dispersion curve approximation.

Figure 15: Final velocity model for the site, ENOC.
### Table 5: Final shear-wave velocity profile measurements.

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<td>1330.64</td>
<td>13.19</td>
</tr>
</tbody>
</table>
7.4.2 Conclusions from Milestone 4

The joint inversion of receiver functions and Rayleigh wave dispersions indicates that this method can be applied successfully for both receiver functions and dispersions that are localized however azimuthal anisotropy needs to be taken into account so as to produce a good match at short periods between observed and synthetic data. The joint inversion results (see Appendix 13.1) suggest there could be a significant intracrustal discontinuity at 2 – 5 km depths across the Central Basin. The receiver functions (Appendix A) show a pronounced sharp versus diffuse pattern of arrivals or multiples and this suggests a variability of anisotropy across the Central Basin.

The results from the MASW measurements were very positive. The technique of combining dispersion curves proved very useful in identifying and confirming features seen in the images. Backwards modelling, using an initial approximation of the velocity model through a first approximation dispersion curve, helped to identify higher modes that were, in fact, needed in some cases. This iterative process also provided confidence in the extracted fundamental mode dispersion curve. Confident velocity models were, therefore, provided.

The method proved useful in identifying the shear-wave velocity in soft sediments found in the graben that was mapped in central Johannesburg. Results from the site, ENOC, confirmed the existence of a low velocity deposit associated with a graben. The shear-wave velocity model transitions from approximately 800 m/s to 1300 m/s at a depth of roughly 40 m. This is interpreted to be the bedrock and is consistent with the graben described in Section 5 of the 2012/2013 Final Report in the SIM 11-02-01 Project. The MASW technique is very useful when considering microzonation studies that seek to identify such zones in anticipation of ground motion amplification.

7.5 MILESTONE 5: Assessment of Expected Damage to Most Representative Buildings in the Johannesburg CBD
The aim of this study is to investigate what the expected damages (losses) to urban structures in the Johannesburg CBD will be due to the seismicity generated by the increased water level in abandoned mines in the Witwatersrand Basin. This estimation is of paramount importance especially in the heavily populated area of Johannesburg that is subjected to natural and/or induced seismic activity. It should be noted that in this section the term ‘seismic event’ includes induced seismic events, triggered seismic events and tectonic origin earthquakes.

The data necessary for the vulnerability assessment of infrastructure unique to South African conditions are, at this time, not available. International methodologies such as ATC-13 and EMS-98 are by far the two most popular procedures. Although most European countries use EMS-98, the majority of the South African agencies prefer ATC-13. Therefore, this report will use the damage factors as defined by Applied Technology Council (ATC-13, 1985) for infrastructures in California.

The classes of building under investigation for the Johannesburg CBD are Unreinforced Masonry, Bearing Wall, Low Rise (Class #3), Rise Reinforced Concrete Shear Wall without Moment Resisting Frame (Class #8) and Reinforced Concrete Shear Wall without Moment Resisting Frame High Rise (Class #9). These three building classes represents approximately 70% of all South African urban structures (Davis and Kijko, 2003). Examples of the identified building classes are shown in Figures. 16-18. The damage matrices (ATC-13, 1985) and vulnerability curves for the three considered classes of building are available in Davies and Kijko (2003), as well as in Report “Risk Assessment due to Seismic Activity for Different Types of Building Classes in the Johannesburg CBD, PART 1: Theoretical Review, ENABLING OUTPUT 4, Project: Fluid-Induced Seismicity in the Central Basin Area: Ground Motion Prediction and the Development of an Early Warning System for Risk Reduction”.

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The problem associated with identification of the most representative classes of buildings in Johannesburg CBD dates back to 2002. At that time, the reinsurance company Hannover RE Africa Limited, approached the Council for Geoscience with request to assess seismic hazard and seismic risk associated with the largest cities in South Africa. In order to classify the urban structures, a structural engineer was commissioned to identify the most representative building classes based on the ATC-13 (1985) requirements. A total of 12 buildings were identified and are discussed in more detail in Table 2 of Davies and Kijko (2003). During the project with Hannover...
Re, the company requested not to make use of images of specific buildings in South Africa. The reason for the request is that by identifying and showing images of particular buildings in a report or article with an associate hazard and risk, will expose the said authors and owners of the buildings to potential liability issues. Especially, if according to our assessments, the structures are exposed to high risk. To avoid any potential liability issues, Milestone 5, therefore illustrates the respectable classes of buildings by making use of generic structures as set out in ATC-13 (1985).

### 7.5.1 Results per Milestone 5

The problem of estimating structural damage arising from a seismic event (seismic risk) for this report is formulated in the similar way as it was done by Cornell (1989; Panel on Earthquake Loss Estimation Methodology, 1989) and Cao et al. (1999). The procedure, probabilistic seismic risk assessment (PSRA), evaluates the probability distributions of all degrees of damages (losses) based on a sample of scenarios. It is considered most appropriate in the light of current knowledge available in South Africa (Kunreuther and Roth, 1998).

The seismic risk assessments for Johannesburg CBD are based on the seismic hazard map representing the 10% probability of exceedance within a 50 year time period (corresponding to return period of 475 years) in terms of peak ground acceleration, unit [g], as provided by the Council for Geoscience, Pretoria (Figure 19).
Figure 19: Seismic hazard map of Johannesburg, representing the 10% probability of exceedance within a 50 year time period in terms of peak ground acceleration, unit [g], as provided by Dr. V. Midzi, Council for Geoscience, Pretoria.

The map of seismic hazard at Figure 17 is crucial, since most of further hazard and risk assessments dependent on this map and its metadata.

At this point in time, we are not questioning the fact that in 50 years’ time, the Johannesburg seismicity pattern can and will be entirely different. It is also true that industries such as engineering, insurance and reinsurance quantify seismic hazard and risk to building structures by assessing the expected damage and losses for return periods 200, 250 and 475 years. For some critical structures such as nuclear power plant, the reference return period is significantly longer, as e.g. 10,000 years. Figure 17 represents an internationally accepted standard in terms of seismic hazard mapping. In other words, it provides the 10% probability of exceedance of the peak ground acceleration within 50 years (or equivalently for return period of 475 years). These numbers were calculated according to the state of the art of seismic hazard assessment procedure, commonly known as the Cornell-McGuire method based on past and current seismic event catalogues. The results and Figure 17 therefore reflects the current seismic activity of the Johannesburg region.
At the same time, Figure 17 doesn't reflect what the seismic hazard and risk levels will be in Johannesburg for example in 25 years. It is therefore of paramount importance to regularly update Figure 17 (say every 2 years). Only then, by analyzing the seismicity and hazard trends over time will we be able to estimate what the seismic hazard and risk will be in the Johannesburg CBD for the years to come.

Twelve maps are created to illustrate the expected damage to the specified classes of buildings typically found in the Johannesburg CBD (Davies and Kijko, 2003). The estimated damage is expressed in terms of the percentage damage to the specified classes of buildings that can be expected with probability of 5% during the next 5, 10, 15 and 25 years, or equivalently, events with return period ca. 100, 200, 300 and 500 years. The probability level of 5% and time intervals 5, 10, 15 and 25 years were chosen to comply with insurance standards where assessments of losses are performed for return periods in the range 100 to 200 years, and engineering standards of hazard assessment usually expressed in terms of return period of ca. 500 years. The calculated damage to the Johannesburg CBD infrastructure can be converted and expressed in monetary terms (Rand) if current monetary value can be associated with each of the investigated building classes.

The investigated area is determined by the area with coordinates latitude [26.115˚S, 26.362˚S] and longitude [27.807˚E, 28.399˚E]. Figures 20 to 31 provide the visual representation of the 12 seismic risk assessments for the investigated area of Johannesburg CBD. For each of the three building classes four maps of percentage expected damage within 5, 10, 15 and 25 years at a 5% probability of exceedance were created.
**Figure 20:** Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 5 years to buildings classified as Unreinforced Masonry, Bearing Wall, Low Rise.
Figure 21: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 5 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame, Medium Rise.
Figure 22: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 5 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame. High Rise.
Figure 23: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 10 years to buildings classified as Unreinforced Masonry, Bearing Wall, Low Rise.
Figure 24: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 10 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame, Medium Rise.
Figure 25: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 10 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame. High Rise.
Figure 26: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 15 years to buildings classified as Unreinforced Masonry, Bearing Wall, Low Rise.
**Figure 27:** Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 15 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame, Medium Rise.
Figure 28: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 15 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame. High Rise.
Figure 29: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 25 years to buildings classified as Unreinforced Masonry, Bearing Wall, Low Rise.
Figure 30: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 25 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame, Medium Rise.
Figure 31: Map of seismic risk for Johannesburg CBD for expected damage of 5% probability within 25 years to buildings classified as Reinforced Concrete Shear Wall without Moment Resisting Frame. High Rise.
7.5.2 Conclusions from Milestone 5

Each of the 12 maps represents the 5% probability of exceedance within periods of 5, 10, 15 and 25 years of the expected damage for three specified building classes in the Johannesburg CBD. The Johannesburg CBD, Germiston and Bedfordview are potentially the three suburbs most affected by seismicity generated by an increase in the water level in abandoned mines in the Witwatersrand Basin. Low rise buildings with unreinforced masonry, bearing wall (building class 3) are in all the investigated cases the most susceptible to damage with an expected damage percentage ranging from 5 to 7%. Comparatively, the expected damage to a building increase over time as the probability of observing a damaging earthquake increases.

The estimated expected damages are small when compared to the damage experience in more seismic active areas or what was observed in countries with devastating earthquakes such as Haiti (12 January 2010) and Nepal (25 April 2015). However, it is important to note since South Africa do not have a database of observed damages due to seismic events, the damage estimates provided in this report are based on international vulnerability curves. The results are therefore only a best estimate.

Damage estimates for houses developed under the governmental Reconstruction and Development Program (RDP) are currently not included in this assessment. The damage estimates for areas such as Soweto and Roodepoort may therefore be significantly higher/lower than reported here. During the recent seismic event Mw 5.5 on 5 August 2014 in Orkney, severe damage was observed to many of RDP houses. Current investigations are underway to build an appropriate damage curve for these infrastructures.
7.6 MILESTONE 6: Velocity models and spatial variation of seismicity in the Central Rand Basin

Velocity Models
Earthquake location is a function of the quality of phase picking, the spatial distribution of network stations, and the seismic velocity model. To improve location accuracy this regional model has to be replaced with a local velocity model (see Midzi et al., 2010). The 17 stations in the CRB record good quality data with clear phases. In this study, ambient noise is used to infer the 1-D Shear-wave velocity (Vs) model for the CRB and clear P-wave arrivals are used to invert for a 1-D P-wave velocity (Vp) model (see Mangongolo, 2011). Both models are used to obtain an average Vp/Vs ratio and relocate earthquakes in the area.

Spatial Variation of seismicity
The topic of fluid induced seismicity in the Central Rand Basin has been raised regularly by the media over the past several years. The actual mechanism of fluid-induced seismicity is not well understood. Most scientists are of the opinion that the induced seismicity is triggered by increased pore pressures in the rock, which reduces the amount of friction on a fault (Sibson 1986; Shapiro et al. 2002; Shapiro et al. 2005).

The identification and description of the evolution of seismicity patterns is regarded as one of the most important approaches in the effort to understand the fluid-induced process. Seismicity is a complex process of substantial spatial and temporal complexity. The report presents and analyses the following parameters: (a) number of earthquakes, (b) cumulative deformation caused by earthquakes, (c) cumulative radiated seismic energy and (d) the largest stress drops associated with seismic events. The results are presented on a map of the CRB. Figure 32 shows a map with the names of old mines in the CRB. The name of the largest mines starting from the left are; Durban Roodepoort Deep, Rand Leases, CMR, Crown Mines, Robinson Deep, City Deep, Simmer and Jack, and ERPM.
7.6.1 Results per Milestone 6

7.6.1.1 Velocity Model

For this study, the data used were P-wave phase arrival picks for earthquakes located in the Central Rand Basin. Only events which were recorded by more than five stations were considered. Only clear first P-wave arrivals were used to minimize errors due to uncertain travel time readings. In total ~860 seismic events of magnitudes M1 ≥ 1.0 recorded in the CRB were used. Before inverting, the phase readings were checked. The result of the inversion for the 1-D P-wave velocities for the upper 5km is presented in Table 6:

Figure 32: Mines in the Central Rand Basin: Durban Roodepoort Deep, Rand Leases, CMR, Crown Mines, Robinson Deep, City Deep, Simmer and Jack, and ERPM.
Table 6: Final P–wave velocity profile for the CRB

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>P-wave velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>4.987</td>
</tr>
<tr>
<td>1.0</td>
<td>5.982</td>
</tr>
<tr>
<td>2.0</td>
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<td>5.984</td>
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<td>6.055</td>
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<td>6.056</td>
</tr>
</tbody>
</table>

Cross correlation of ambient noise recorded at two stations was used to retrieve the Green’s function between the two stations. In other words, measuring the cross-correlation of noise at station A with noise at station B is equivalent to recording a signal generated at station A by an impulse excitation at station B. The surface wave part of that noise cross-correlation Green’s function (NCF) is used to retrieve the dispersion curve, which is inverted for shear-wave velocity. To infer the 1-D Shear-wave velocity model, group velocity dispersion curves were calculated for each station pair. All dispersion curves were averaged and the average obtained was used to invert for a 1-D velocity model. This methodology was applied to 17 stations installed in the CRB. Continuous (1 day long) waveforms from the vertical-components of the stations were retrieved from the waveform database and cut into 30 minute segments using 75% overlap. The daily cross correlation functions (CCF) that were obtained were stacked to form Green’s functions for each station pair. Only the vertical-components of the ambient noise were used.

CCF computed for each pair of stations show a perfect reconstruction of the Green’s functions. One can see that the causal part (from time lag 0 to 100) is symmetric to a causal part (negative time from 0 to -100) (see Figure 33). The Green’s functions show prominent phase arrivals traveling with apparent velocities of approximately 2.5 km/s.
Figure 33: Phase identification on the Green’s functions. The prominent arrivals are surface-waves. They are Rayleigh waves travelling with a velocity of 2.5 km/s

The dispersion curves obtained for each station pair showed that group velocities were between 2.2 and 2.8 km/s for periods ranging from 0.8 to 3 sec. The average dispersion curve (Figure 34) was calculated by stacking the dispersion curves for all station pairs in the area.
Figure 34: The dispersion curves calculated in the CRB with the average dispersion curve shown in green. The group velocity is between 2.2 and 2.8 km/s.

The average dispersion curve was then used to invert for the 1-D shear-wave velocity profile. The longest period on the average dispersion curve is 3 sec. At that period, only the upper 4-5 km can be resolved. The result of the inversion of the average dispersion curve is a 1-D Shear-wave velocity profile for the CRB. The shear-wave velocities range from +/- 2.6km/s to +/-3.55km/s (see Figure 35 and Table 7). Considering the interstation distance, the data is not able to reliably resolve structure at depths shallower than 1.0 km.
Figure 35: Group velocity dispersion curve and shear-wave velocity inversion result for Central Rand.

Table 7: Final shear–wave velocity profile for the CRB

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Shear-wave velocity (km/s)</th>
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<td>1.0</td>
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<tr>
<td>2.0</td>
<td>3.3597</td>
</tr>
<tr>
<td>3.0</td>
<td>3.3815</td>
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<tr>
<td>4.0</td>
<td>3.5300</td>
</tr>
</tbody>
</table>

Using P-wave arrivals and ambient noise, we obtained P-wave and S-wave velocity profiles independently for the upper 5km of crust in the CRB. To test the final velocity model, events were relocated in the CRB using the double difference technique.
This technique requires a P-wave velocity model and Vp/Vs ratio. A comparison was made against results from the relocation when using the Midzi et al. (2010) model. Using the new model, 62% of the events were concentrated within the expected seismogenic depth of 5 km for mining events. The improvement suggests that it is advisable to use multiple layers for the upper 5 km of crust when defining a local velocity model. Using a one layered model pushes the event locations deeper than expected. Using our model, the errors in longitude, latitude and depth, range from 56.1 to 800 m, 27.4 to 850 m and 53.5 to 900 m, respectively. While using the Midzi et al. (2010) model, the errors in longitude, latitude and depth, range between 125.0 and 1112.3 m, 90.0 and 1060.0 m and 650.0 and 2460.0 m, respectively. Earthquake hypocenters calculated using Midzi et al. (2010) have larger errors in depth (~ 2 to 3 times) compared to our model. This also shows that having a multi-layered model for the upper 5 km decreases the error in depth. Events outside the mining area were not considered in our analysis.

### 7.6.1.2 Seismicity pattern in the Central Rand Basin during last five years

Spatial characteristics of the seismicity pattern were progressively analyzed on an annual basis. Two previous reports compiled under this project presented the evolution of seismicity for the period March 2010 to November 2011 (Cichowicz et. al. 2012 report entitled “Spatial variation of seismicity in the Central Basin 2011”) and March 2010 to November 2012 (Cichowicz et Al. 2013 report entitled “Temporal and Spatial Variation of Seismicity and in the Central Rand Basin 2012”). This report presents a continuation using new data. The current study focused on an extended period of more than five years from 01 March 2010 to 27 May 2015. The analysis described in the first report was based on a catalogue of 573 events and in the second report, a catalogue of almost 1000 earthquakes. This study, the final catalogue presented in this project, has 2863 events.

Seismic events are recorded by a variable number of seismic stations. It is well understood that small events are only recorded by a few close-by stations and the
strongest events should be recorded by the entire network. To evaluate the dynamics of the activity in the area, all seismic events need to be considered. However, for the identification of active areas in the CRB, only well located events can be used.

A seismic station that records an event is said to have triggered. The relationship between the number of triggers and accuracy of location is obvious - seismic events that are recorded by one or three seismic stations are less accurately located compared to events recorded by six or more stations. Numbers of triggers is not the only controlling factor influencing accuracy of location but it is a useful indicator when classifying events. A minimum of six triggers per event was used to improve the catalogue for further analysis of changes in the seismicity pattern with respect to space and time.

The spatial evolution of the seismicity over the last five years is displayed in Figure 36. From top to bottom, the seismicity pattern is presented in snapshots of 12 months from 27 May 2010 to 27 May 2011, 27 May 2011 to 27 May 2012, 27 May 2012 to 27 May 2013, 27 May 2013 to 27 May 2014 and 27 May 2014 to 27 May 2015. The distribution of seismicity shows that the eastern part of the CRB in the area of the ERPM mine voids is still the most active region. The northern parts of the ERPM mine and Rose Deep mine in Germiston was active during 2013 and 2014 but near the end of 2014 and beginning of 2015, activity subsided.

Fresh activity was observed south of Durban Roodepoort Deep mine during 2014 and 2015. This cluster was not present during the initial periods of fluid-induced seismicity between 2010 and 2013. The area is associated with active mining at the Doornkop and Cooke mines. In addition, according to national news headlines, illegal mining operations that can reach depths of up to 1000 m are taking place at the South Roodepoort and DRD mines. Doornkop comprises a single shaft system of intermediate depth (maximum depth of 1 973m). The operation focuses on narrow-reef conventional mining of the South Reef. The Cooke operation is shallow at a depth of about 1000m. The depths of the seismic events vary from surface to a few
kilometers. Over 150 events were observed south of DRD with the two largest events each having an approximate magnitude of 2.5. The seismic activity started in 2013 but most of the events occurred between 2014 and 2015. The cumulative seismic moment is $0.5 \times 10^{14}$ Nm.

The areas which include Crown Mines, Robinson Deep and City Deep mines were active throughout the five years of monitoring and there is no observed reduction in the level of seismicity. The increased level of seismicity in the northern parts of the Simmer and Jack and surrounding mines was identified and highlighted as an area of concern in the report of enabling output 6 in the 2012/2013 year of this project entitled “Stress modelling in mining areas – identifying zones of seismic potential”. Relocated seismicity recorded between 2010 and 2012 was plotted on a detailed map of the in-mine geology mapped by Pretorius (circa 1970). The high level of seismic activity coincided with geological features in this region that proved most likely to fail under conditions related to flooding in the mines (see Figures 14 and 15 in Enabling Output 6, “Stress modelling in mining areas – identifying zones of seismic potential”, 2013).

Figure 37 is a cropped image of the shareholder plans provided by DMR for Central Rand Basin mines. In the northern parts of the simmer and jack mine a number of dykes intersect along three dominant directions creating “tri-angles” whereas in the southern parts of the mine the dykes are plotted as mostly parallel. The large “Simmer Dyke” in the north east corner of the Simmer and Jack mine extending from the Rose Deep mine also falls within this region of high seismic activity.

Over the last three years, a cluster of seismic events has extended south of Crown Mines and Robinson Deep mine. The cluster is located outside of the areas delineated by mine boundaries; therefore, the underground geology of the area could not be studied. The cluster is not associated with any known surface faults or dykes (see Figures 36 and 38, blue lines). Most of the events have magnitudes smaller than one and the strongest event has a magnitude of 1.6. The cluster has events with very small stress drops, less than 1 MPa. The event depths suggest that source of the disturbance is located close to or on the surface. The cluster of about 20 events
could be associated with superficial activities, however, the scattering of the seismic event locations does not allow for the association of the seismicity with a specific type of activity, although, a large quarry is located within the cluster.
Figure 36: Evolution of the seismicity pattern over a five year period. From top to bottom, the seismicity pattern is presented in snapshots of 12 months from 27 May 2010 to 27 May 2011, 27 May 2011 to 27 May 2012, 27 May 2012 to 27 May 2013, 27 May 2013 to 27 May 2014 and 27 May 2014 to 27 May 2015.
Figure 37: A cropped image of the shareholder plans provided by DMR for Central Rand Basin mines.

Figure 38 shows the distribution of seismicity in the CRB in two snapshots. The first snapshot shows the spatial distribution of events with respect to magnitude from when monitoring with the extended seismic network started (see Figure 38 top). The second snapshot displays the seismicity that occurred in the last two years starting from 27 March 2013 to 27 May 2015 (see Figure 37 bottom). The sizes of the dots are proportional to moment magnitude $M_w$. The delineation of the surface faults (blue lines) was obtained from the corporate spatial database of the Council for Geoscience. The data, that covers most parts of South Africa, was taken from the 1:50 000 geological databases.

The biggest events with magnitudes greater than three are located in the eastern part of the CRB, specifically in the southern part of the ERPM mine. That part of the mine was the last to close in the CRB as a whole, in November of 2008. Crown Mines, Robinson Deep and City Deep mines have been very active over the last five years
but the magnitudes of the seismic events were small, below 2.5. All of the events of $M_L$ 3 and larger occurred solely in the eastern part of the basin prior to 2013 (Figure 38 (top)). However, the largest seismic event with magnitude $M_w$ 3.4 ($M_L$ 3.6) was located in the western part of the CRB (Figure 37 (bottom)). The event on 18 November 2013 was felt from the Johannesburg City Centre all the way across to the West Rand. The source of the event was located just north of the University of Johannesburg. Events of this nature have and continue to generate a lot of public interest due to reports from the public who have felt the tremors.

Birch (2013) studied vulnerabilities in the CRB seismotectonic model using 3D modelling and a wealth of geological information collected underground in the mines. This would not have been available through studies on the surface. A relationship was found between the orientations of the mined out reef and the intersecting geology. This provided an explanation for the high level of seismic activity observed in the central and eastern parts of the CRB. The study showed that structures associated with left-lateral strike-slip faults were exclusively indicated in the region of ERPM citing this as a possible reason why the largest events had occurred there. ERPM was also the last mine to stop pumping and, therefore, has had less time to release residual mining-induced stresses. In spite of this information, the largest event was later measured in the western part of the CRB, showing that although this area had been flooded much earlier, large events were still possible.

The cluster of seismic events to the south of the Crown Mines and Robinson Deep mine is dominated by small magnitude events and is not associated with any known surface fault.
Final Report on SIM 14-02-05 “Fluid-Induced Seismicity in the Central Basin Area”

<table>
<thead>
<tr>
<th>Z [km]</th>
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<td>28</td>
<td>3.5</td>
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<td>5</td>
</tr>
<tr>
<td>28.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Diagram shows seismic activity with a time window from 2010-03-27 to 2015-05-27.
Figure 38: (top) Distribution of seismicity over a five year period from 27 May 2010 to 27 May 2015 - plan view and two vertical cross sections. (bottom) Distribution of seismicity over the last two years from 27 May 2013 to 27 May 2015. The size of the dots is proportional to moment magnitude $M_w$. Known surface faults are marked with blue lines.

7.6.1.3 Cumulative seismic deformation in the Central Rand Basin

The magnitude of the scalar seismic moment can be viewed as an approximation to the regional changes of shear strain in response to seismicity. The scalar seismic moment is a measure of the strain induced by a seismic event. A measure of the seismic deformation released is obtained from the cumulative seismic moment of all
seismic events recorded in an area (McGarr, 1976). The dominant contribution to the scalar seismic moment is from the largest earthquakes. An analysis of the spatial and temporal distribution of the cumulative seismic moment is presented below.

The spatial variation of seismicity is studied by dividing the Central Rand Basin into polygons of equal areas. The main motivation for selecting polygons is finding the spatial distribution of centres of seismicity in terms of the number of observed events, the radiated seismic energy and the cumulative seismic deformation. In 2010 when a network of strong ground motion sensors was installed it was not known where the centres of seismicity were located. The concern was that the seismicity could migrate outside of the mining areas through the re-activation of some geological features. A simple plot of event locations and their parameters is not sufficient to evaluate, in quantitative way, the spatial cumulative seismic moment or radiated seismic energy. The solution to the problem was the concept of finding, without any pre-defined limits, the centres of seismic deformation. The seismicity fluctuations in space are studied by dividing the Central Rand Basin into polygons of equal area. All polygons that have at least one earthquake per polygon are marked as active polygons and for all active polygons the cumulative value of the seismic parameters are calculated.

In 2010-2011, when the strong ground motion network started to provide data, the Central Rand Basin was divided into polygons of different sizes. The suitability of the following three sizes of polygons was investigated: 10 km x 10km, 4 km x 4 km and 2 km x 2 km (year 1, milestone 6: “Spatial variation of seismicity in the Central Basin 2011” section 3.2 “Identification Polygons with Dense Seismicity”). The small polygons were used to identify all possible areas of increased seismicity. The larger polygons were more suitable for the calculation of the cumulative seismic parameters. Milestone 6 “Velocity models and spatial variation of seismicity in the Central Rand Basin” provides an analysis of the cumulative number of seismic events per polygon, the cumulative seismic moment per polygon and the cumulative seismic energy per polygon. This summary report (Milestone 8) is focused on the investigation of the cumulative seismic moment per polygon.
In this report, the spatial variation of the seismicity was studied by dividing the Central Rand Basin into polygons of 7 km x 7 km. The number of earthquakes per polygon is shown in Figures 36, 37, 38 and 39 (tops). Over a five year, 40 polygons formed and were distributed equally across the Central Rand Basin. In the first two years, the number of polygons was lower, 23, while over the next two years, from 27 May 2012 to 27 May 2014, the number of seismically active polygons increased to 39. The fifth and final year in this study produced only 23 active polygons. The characteristics of the spatial variation throughout the five year period are described in the paragraphs below. In general, the seismicity was concentrated in a small number of polygons, while some scattered epicenters also exist.

**Period from 27 May 2010 to 27 May 2015:**
The selected catalog consists of 1115 seismic events, well recorded by at least 6 seismograph stations. The total cumulative seismic moment released in the CRB was $9.0 \times 10^{14}$ Nm. This is equivalent of one earthquake of magnitude $M_w$ 3.9. The polygons with the largest number of events observed are located in the northern parts of the ERPM and Simmer and Jack mines. The three largest polygons occur in this area and together account for approximately 500 events (Figure 39 (bottom)). Two polygons accounted for the bulk of the cumulative seismic moment, which also plot in the ERPM and Simmer and Jack mines. These two polygons have a combined cumulative seismic moment in the order of $4 \times 10^{14}$ Nm, equivalent to one event of magnitude $M_w$ 3.6. Low activity was observed around the CMR mine with less than 20 events in this period; however, this includes one very large event of magnitude $M_w$ 3.4 ($M_L$ 3.6).

**Period from 27 May 2010 to 27 May 2012:**
The selected catalog has 157 seismic events with a cumulative seismic moment of $2.17 \times 10^{14}$ Nm, equivalent to one earthquake of $M_w$ 3.49. The cumulative seismic moment observed in the first two years of monitoring has a similar pattern to that observed over five years. However, during this period, less than 100 events were
recorded in the ERPM and Simmer and Jack mines with a cumulative seismic moment of \( \sim 1.4 \times 10^{14} \) Nm, equivalent to a magnitude \( M_w 3.36 \) (see Figure 40 (bottom)). It should be noted that during this period, only 13 polygons were active.

**Period from 27 May 2012 to 27 May 2014:**

The selected catalog has 665 seismic events with a cumulative seismic moment of \( 3.52 \times 10^{14} \) Nm, equivalent to an earthquake of \( M_w 3.63 \). The seismicity pattern in terms of number of events (Figure 41 (top)) shows similar characteristics when compared with Figures 36 and 37. The three polygons over the ERPM and Simmer and Jack mines account for approximately 300 events. However, the total number of active polygons increased from 13 in Figure 39 to 42. This increase is associated with seismic activity in the western and eastern parts of the CRB. The change in the number of active polygons could partially be attributed to an improved configuration of the seismic stations and the implementation of an advanced seismic data acquisition system, which took place in August 2012. The cumulative seismic moment over ERPM and Simmer and Jack mines is \( 1.6 \times 10^{14} \) Nm, which is similar to the value observed between 2010 and 2012 (Figure 41 (bottom)). The most notable difference is the seismic moment that was released during a single event near CMR mine of \( 0.8 \times 10^{14} \) Nm.

**Period from 27 May 2014 to 27 May 2015:**

Figure 42(bottom) shows the cumulative seismic deformation observed over the last year. The selected catalog has 290 seismic events with a cumulative seismic moment of \( 0.86 \times 10^{14} \) Nm. The three biggest clusters, again in the ERPM and Simmer and Jack mines, account for approximately 100 events with a cumulative seismic moment of \( 0.1 \times 10^{14} \) Nm. The values of number of events and cumulative seismic moment are smaller than was observed over the previous two years. The biggest event was located outside of the CRB with a seismic moment of \( 0.86 \times 10^{14} \) Nm. The reduction in seismicity is significant even after normalizing each map to the equivalent of one year time periods.
Figure 39: Cumulative seismic moment in the CRB observed over a five year period from 27 May 2010 to 27 May 2015. (top) The CRB was divided into equally sized polygons of 7 km x 7 km. The size and colour of the dots reflect the number of earthquakes per polygon. (bottom) Cumulative deformation per polygon where the size of the dots is proportional to the cumulative seismic moment released per polygon.
Number of Polygons = 13  
Polygon Area = 49 km²
Figure 40: Cumulative seismic moment in the Central Rand Basin observed over a two year period from 27 May 2010 to 27 May 2012. (top) The CRB was divided into equally sized polygons of 7 km x 7 km. The size and colour of the dots reflect the number of earthquakes per polygon. (bottom) Cumulative deformation per polygon where the size of the dots is proportional to the cumulative seismic moment released per polygon.
Number of Polygons = 39   Polygon Area = 49 km²

Number of Events per Polygon

10  20  30  40  50  60  70  80  90  100  110

Figure 41: Cumulative seismic moment in the CRB observed over a two year period from 27 May 2012 to 27 May 2014. (top) The CRB was divided into equally sized polygons of 7 km x 7 km. The size and colour of the dots reflect the number of earthquakes per polygon. (bottom) Cumulative deformation per polygon where the size of the dots is proportional to the cumulative seismic moment released per polygon.
Number of Polygons = 23   Polygon Area = 49 km²
Figure 42: Cumulative seismic moment in the CRB observed in the last year from 27 May 2014 to 27 May 2015. (top) The CRB was divided into equally sized polygons of 7 km x 7 km. The size and colour of the dots reflect the number of earthquakes per polygon. (bottom) Cumulative deformation per polygon where the size of the dots is proportional to the cumulative seismic moment released per polygon.
7.6.1.4 Static Stress Drop

The spatial distribution of static stress drop is shown in Figures 43 and 44. The earthquakes with the largest stress drops, up to 10MPa, were observed in the eastern parts of the CRB (ERPM mine area). These high stress drop events are responsible for strong ground motion. Most events register static stress drop values smaller than 5MPa. The spatial distribution pattern of large static stress drop events did not change much over the last year. The largest event, which measured a static stress drop of 43MPa, was recorded in the western part the Central Rand Basin. This event was most likely related to mining and could not be classified as fluid-induced seismicity.
Figure 43: Distribution of the measured static stress drop in a five year period from 27 May 2010 to 27 May 2015. The size and colour of the dots is proportional to the value of the static stress drop. The horizontal colour scale is measured in MPa.
Figure 44: Distribution of the measured static stress drop for the most recent year from 27 May 2014 to 27 May 2015. The size and colour of the dots is proportional to the value of the static stress drop. The horizontal colour scale is measured in MPa.

7.6.2 Conclusions from Milestone 6

The accuracy of event locations is strongly affected by the velocity model used to describe the upper parts of the crust. The P-wave first arrival and ambient noise techniques were applied to obtain a new velocity model for the upper 5 km of crust,
which significantly improved the location of seismic events in the CRB as most of the events originate within this structure.

The spatial and temporal variation of the seismicity in the CRB experienced over a period of five years was analyzed. The observed seismicity patterns were strongly related to the presence of old mining voids. Strong evidence to suggest that the seismicity is migrating to areas outside of previous mining boundaries could not be found with the exception of one small cluster. The following patterns emerged: (1) the distribution of seismicity shows that the eastern part of the CRB is still the most active region. (2) The northern parts of the ERPM mine and the Rose Deep Germiston mine were active during 2013 and 2014 but near the end of 2014 and beginning of 2015, activity subsided. (3) New activity arose south of the Durban Roodepoort Deep mine during 2014 and 2015. (4) The areas, which include Crown Mines, Robinson Deep and City Deep mines are active throughout the five year and there is no evidence to suggest that the level of seismicity is decreasing. (5) Over the last three years a cluster of seismicity has developed, which extends to the south of Crown Mines and Robinson Deep mine. The cluster is located outside of the area delineated by mine boundaries and a large quarry is located within the cluster. (6) Strong seismicity was observed southwest of the Durban Roodepoort Deep mine. It is related to current mining activities.

The dynamic forces in the area, which influence seismicity, are fluctuating. The evolution of the seismicity pattern over time indicates that the CRB is still in an unstable state. The actual mechanism of fluid induced seismicity is not well understood. Most scientists are of the opinion that the seismicity is triggered by an increase in pore pressure in the rock mass, which reduces the frictional force on a fault.

The total cumulative seismic moment released in the CRB over the last five years is $9 \times 10^{14}$ Nm, which is equivalent to a single earthquake with a magnitude of $M_w$ 3.9.
This is significantly less than what was observed during active mining on the CRB. In 1972 a magnitude $M_w$ 4.8 earthquake struck in the ERPM mine.

The spatial and temporal variations in the level of seismicity, seismic moment, radiated seismic energy and static stress drop were presented for the CRB. The seismic moment strongly correlates with the seismic energy, therefore, a similar evolution in space and time of these parameters was observed. The number of events per polygon does not relate to the cumulative seismic moment or radiated seismic energy. The earthquakes with the largest stress drops were recorded in the eastern and central parts of the CRB.

### 7.7 MILESTONE 7: Spectral parameters of the seismic sources and their temporal variation in the Central Rand Basin

The characterization of seismicity triggered by a rising water level in the Central Rand Basin was achieved through the estimation of source parameters. The relations between spectral parameters of the seismic source are presented for events recorded between 2010 and 2015. These relationships will aid in the understanding of physical phenomena that occur in the medium due to flooding. The fundamental question that is to be answered is; how does fluid-induced seismicity in the Central Rand Basin change over time? The characterization of seismicity triggered by a rising water level in the Central Rand Basin is achieved through the estimation of source parameters. The relations between source parameters provide an understanding of physical phenomena that occur in the medium due to flooding.

#### 7.7.1 Results per Milestone 7
7.7.1.1 Spectral parameters of the seismic sources

The attenuation of seismic waves is a very important parameter in the assessment of earthquake source parameters. The attenuation of the P- and S-waves in the Central Rand Basin was estimated using the coda normalization method (Cichowicz & Birch, 2010). The events used in the estimations were filtered in a frequency ranging from 3 to 32 Hz. This frequency limitation was imposed because the initial sampling rate of ground motion was 100Hz. Thus, the estimations of the S- and P-wave quality factors are \( Q_s(f) = 43f^{0.87} \) and \( Q_P(f) = 20f^{0.9} \), respectively. Spectral analysis is performed in the frequency range 0.2 – 80Hz. This is made possible by the recent switch to a 200 Hz sampling rate at all of the seismic stations. Since an estimation of the quality factor using coda normalization did not cover the full range of frequencies, an extrapolation had to be made from 32Hz to 80Hz. Two models were selected as possible candidates. The first model is based on the coda normalization method that was described above, the second model uses a quality factor of \( Q_s = 400 \). The motivation for the second model is based on the fact that \( Q_s \) is constant in several applications of the spectral analysis. This value of 400 is the average over the frequency dependent relationship and a similar value is used by underground mining networks. The choice of the attenuation model influences the high frequency signal, e.g. above corner frequency, but does not disrupt the estimation of scalar seismic moment, which utilizes the low frequency part of the spectrum. All seismic stations are located on hard rock; therefore, kappa is assumed small and was set to a value of 0.005. Figure 42 shows the relationship between scalar seismic moment and corner frequency obtained for the two models of attenuation, \( Q = \text{constant} \) and \( Q(f) = \text{frequency dependent} \). The values of scalar seismic moment are not influenced as the measurement is based on the low frequency part of the signal. The corner frequencies are affected by the assumed model of attenuation. Therefore, the two graphs in Figure 45 appear different. The static stress drop for a model with frequency dependent attenuation provides values that are more realistic; therefore, this was used for further interpretation.
Figure 45 shows seismic moment versus corner frequencies for two components of the S-waves. Diagonal lines follow constant stress drops. Similar relationships were reported by Cichowicz et al. (2012). Cichowicz et al. (2012) utilized all data recorded between March 2010 and November 2012. The current report is based on data recorded between 1 March 2010 and 26 May 2015, but there is a significant difference in the quality filter applied in the current study. The quality filter accepts, for processing only, events recorded by a minimum of six seismic stations. Application of the quality filter reduced scattering in the graphs presented in Figure 42. Good quality data clearly shows that the static stress drop is between 10MPa and 0.05MPa. The data show that large static stress drop is not only associated with large events, but also with small events. The observed corner frequencies vary from 7 Hz to 60 Hz. The SH-wave could be strongly affected by near surface geology in comparison to the SV-wave. Therefore, the SV component of an S-wave is preferred for use in interpreting values of the seismic source parameters.
Figure 45: The relationship between scalar seismic moments versus corner frequencies for the S-waves. Two different models of the quality factor were used for spectra correction: (top) $Q(f) = Q_s(f) = 43 f^{0.87}$ (bottom) $Q = 400$.

Figure 46 shows the relationships between the scalar seismic moment components and the static stress drops. The static stress drop values for most of the seismic events vary by less than 2 orders, while the scalar seismic moments vary by less than 4 orders. Cichowicz et al. (2012) concluded that an increase in the static stress drop is associated with an increase in the seismic moment. The good quality data presented in Figure 45 allows for a more precise conclusion. The static stress drop increases with an increase in the seismic moment for seismic moments ranging from $10^{10}$ Nm to $10^{13}$ Nm. However, for seismic moments larger than $10^{13}$ Nm the upper limit for the static stress drop is 10MPa (excluding 2 outliers).
Figure 46: The relationship between static stress drops, $\Delta \sigma_s$, versus seismic moments and for the S-waves. The relationship obtained for the SV component.

7.7.1.2 Moment tensor inversion

The moment tensor inversion results were obtained using a computer programme that was developed by Ngobeni (2015). Only four events were examined because they fitted the criteria set out for a reliable moment tensor inversion. The criteria set out was that there should be plausible azimuthal station coverage for the event, and since the software requires first motion polarities to distinguish between two moment tensor solutions due to the inversion of spectral amplitudes, the events to be examined had to have at least four clear first motion polarities. The inversion results of the four events studied show significant non-double-couple (non-DC) components
(Table 8). The fault plane solutions for events 1 and 2 show strike-slip mechanisms with large reverse components (see Figures 47 and 48 (a)). Events 3 and 4 show strike-slip mechanisms with small reverse or normal components (see Figure 48 (b) and Figure 49). The azimuth of the T axis for events 1, 2, and 3 is in the North-East and that of the P axis is in the North-West. However, for event 4, the azimuth of the P axis is in the North-East and the T axis is oriented in the North-West.

### Table 8  Moment tensor parameters

<table>
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<tr>
<th>Event</th>
<th>Mag</th>
<th>Date</th>
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<th>CLVD</th>
<th>DC</th>
<th>Depth</th>
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<td>-30.1</td>
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Event 1 is located in the vicinity of a northerly striking fault, and the focal mechanism shows that one of the nodal planes is striking a nearly northerly direction (Figure 47). Event 2 is located near an easterly striking fault, but none of the nodal planes is striking in the same direction as the fault, at best, one of the nodal planes is striking in the north-westerly direction (Figure 48(a)). It is possible that event 2 was not due to the easterly striking fault because location of events is not as accurate. Event 3 is located ~50 meters north of an easterly striking fault, and the focal mechanisms show that one of the nodal planes is also striking in the easterly direction (Figure 48(b)). Event 4 is located at an intersection of two faults, one striking in the north-of-northeast and the other striking in the southeast (Figure 49). Consistent with the observed faults, the fault plane solution of event 4 has one nodal plane that strikes in the north-of-northeast, and the other nodal plane is striking in the southeast.
Figure 47: Fault plane solution for event 1 using lower-hemisphere projection. The shaded area denotes the Tensional quadrant, while the unshaded area denotes the compressional quadrant. Crosses denote upward first motion, and dashes denote downward first motion. The purple lines on the map depict observed faults, and the red dot is the location of the event.
**Figure 48:** Fault plane solutions for events 2 marked as (a) and event 3 marked as (b).
Figure 49: Fault plane solution for event 4. The question mark indicates unclear first motion.

The moment tensors retrieved for events 1 and 3 show significant non-DC components owing to the large compensated vector linear dipole (CLVD) component, which according to Vavryčuk (2011) and Stierle et al. (2014), it is more sensitive to errors in the moment tensor. The non-DC components contain both the isotropic (ISO) and CLVD components, which are positive for event 1 and negative for event 3. According to Vavryčuk (2001), both the ISO and CLVD components are positive for tensile (volumetric increase) faulting and negative for implosional (volumetric decrease) faulting. Events 2 and 4 show significant double-couple (DC) components with small ISO components, whose accuracy is twice that of the CLVD and DC (Vavryčuk, 2011).
According to Vavryčuk et al. (2008), complex faulting cannot generate an ISO component, thus if the ISO components in all the events studied represent some physical phenomena, then the non-DC cannot be explained using the complex faulting model. Thus, events 1 and 2 may have been caused by sufficiently high pore pressure in the fault, which can open the fault during an event resulting in mechanisms with a combination of shear and tensile faulting (Vavryčuk et al., 2008); and since there is evidence of flooding in the now defunct mines of the Central Rand Goldfields, tensile faulting seems to be a more favorable explanation of the origins of the non-DC for events 1 and 2. Event 3 is preceded by a tensile mechanism of event 2, so, it may be possible that radiated energy from event 2 caused closure on the fault that gave rise to event 3, since they are ~400 meters apart, hence the volumetric decrease. Event 4 occurred at a vicinity of an intersection of two faults, and as such, it may be possible that the volumetric decrease took place, because according to Juian et al. (1998), if a tensile fault and a shear fault intersect, then stick-slip instability could cause sudden episodes of volumetric increases or decreases.

The high values of the CLVD component may indicate that the tensile and implosional faulting may not be the predominant origins of the non-DC components. Other possible origins of the non-DC may include (1) errors in the retrieval of the moment tensor due to noise and data limitations of the input data, (2) anisotropy in the focal area, and (3) inaccurate Green’s functions due to poor knowledge of the velocity model.

7.7.1.3 Seismicity rate in events per month

The level of seismicity in the Central Rand Basin is not decreasing. The number of large events, with $M_w$ magnitudes above 2.0, 1.8, 1.6 and 1.4, is still as high as it was when monitoring began over five years ago according to two-sample t-test with the 95% confidence level. There were several stages of increases and decreases seismicity over the five year monitoring period.
Seismicity in a particular region is categorised by the number of events per unit time. Figure 50 shows histograms of the number of events per 30 days over a five year period; each event was located by at least three seismograph stations. The observed seismic event data were divided into four intervals and the mean value was determined for each interval. Due to the nature of this investigation, the analysis is not intended to produce a particular number for the mean value. Instead, a range of mean values was estimated. This range of values is called a confidence interval, CI. The confidence interval for the mean value helps to estimate the true population mean. The most widely used value for the confidence level is 95%. The correct interpretation of the CI is that there is a 95% probability that the confidence interval contains the true value of the population mean. Confidence intervals provide more information than point estimates. Confidence intervals (CIs) are used to compare the true means of two populations in the following way: if two 95% CIs overlap, then it can be concluded that the two population means are the same or when only one CI is available from one of the populations. It can be concluded that the two means are equal if the one sample mean is within the 95% CI of the others mean (e.g. Lo, 1994).

There are a large number of publications, which suggest different statistical procedures for comparing the true mean of two populations. These are based on the difference between two means and the ratio of two means. There is no consensus that one method is better than another, therefore, a comparison of the CIs for each of the four intervals and a two-sample t-test with the 95% confidence level was chosen. A two-sample t-test would guide the decision process.

A two-sample t-test is a parametric test that compares the mean parameter of two independent populations $X_1$ and $X_2$. The difference between two means determined from small sample numbers follows the t-distribution. The test statistic is

$$ t = \frac{x_1 - x_2}{s_p \sqrt{\frac{1}{n} + \frac{1}{m}}} $$
where $x_1$ and $x_2$ are the sample means, $s_1$ and $s_2$ are the sample standard deviations, and $n$ and $m$ are the sample sizes. The test tests the null hypothesis that two data vector vectors $X_1$ and $X_2$ come from populations with equal means (Rowe, 2001). The result is ‘1’ if the test rejects the null hypothesis at the 95% significance level. A value of ‘0’ indicates that the test does not reject the null hypothesis at the default 95% significance level (MATLAB function ttest2).

The magnitude of completeness was established as $M_w = 1.3$ for the catalogue. The exact value of the magnitude of the completeness will depend on the method applied. To avoid a discussion on this issue, arbitrary large magnitudes, $M_w 2, 1.8, 1.6$ and $1.4$ were chosen for the analysis, which are larger than the magnitude of completeness. Figure 50 shows a bar chart of the seismicity rate over a period of 62 months for events. Data are divided into four intervals of 16 months with a one month overlap. Bar charts of the seismicity rate are displayed for four different thresholds of maximum magnitude (from top figure to bottom: $M_w 2.0, 1.8, 1.6$ and $1.4$). The mean values for each interval are marked with a blue line. The confidence intervals (CI) are marked with red lines.

A comparison of the four confidence intervals clearly shows that each 95% CI overlaps with the remaining three (see Figure 50). Table 9 shows 24 results of two-sample $t$-tests. The four intervals of 16 months are named A, B, C and D, respectively. The two-sample $t$-tests were performed for all combinations of intervals and for four different magnitudes. The mean values of two intervals are the same with 95% confidence when the test result is ‘0’. The result ‘1’ indicates that the two means are different. The results for most of the tests show that at the 95% confidence level these means are not statistically different. A systematic feature is that interval B for $M_w 1.6$ and $1.4$ has a lower mean value than the rest of the intervals. Hence, the conclusion, that the seismicity rate does not show signs of decreasing when examining the numbers of events recorded over the last five years. Instead a variation in the level of seismicity was observed.
Figure 50: Bar chart of the seismicity rate over a period of 62 months. Data are divided into four intervals of 16 months with a one month overlap. The mean values for each interval are marked with blue lines and the confidence intervals are marked with red lines. Bar charts of the seismicity rate are displayed for four different thresholds of maximum magnitude (from top figure to bottom: $M_w$ 2.0, 1.8, 1.6 and 1.4).
Table 9: The results of the two-sample t-tests. The four intervals of 16 months are named A, B, C and D, respectively. The two-sample t-tests were performed for all combinations of intervals using different magnitudes. The mean values of two intervals are the same with 95% confidence when the result is ‘0’ and different when the result is ‘1’.

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7.7.1.4 Cumulative seismic rate, seismic moment and seismic energy

Temporal variation of spectral parameters in the Central Rand Basin

Tectonic loading or induced loading is responsible for stress perturbation and, if applied to a fault population, produces a change in the seismicity rate (Dieterich, 1994). The rate of earthquake occurrence is proportional to the monotonic stress increase. Dieterich (1994) found that the seismicity rate seeks a steady state value that is proportional to the instantaneous stressing rate. Consequently, a relatively modest jump in stress results in very large perturbations in earthquake activity. Since
any loading history may be represented as a sequence of small stress jumps, a
distribution of slip speeds can be plotted to observe changes in the seismicity rate.
Gomberg et al. (2005) studied models of seismicity rate changes caused by the
application of a static stress perturbation to a population of faults. They showed that
seismicity rate changes depend on fault maturity, which is highest for faults closest to
failure.

The correlation of changes in earthquake activity with stress led to suggestions that
stress changes might be calculated from earthquake occurrence rates (Dieterich et
al., 2000). The purpose of this study is to identify any anomalous changes in the
seismic activity rate using the method of cumulative number of events. The linear
behavior of the cumulative number of events plot is an indication of stationary
occurrence. In order to quantify a stationary stage for a given window, a seismic rate
is calculated as the number of earthquakes divided by the time covered by the
window. The periods with a constant slope define the mean background rate. In
contrast, non-stationary behavior is defined as a rapid change in the seismic activity
rate.

Figure 51 shows the cumulative number of earthquakes versus time for all events
with magnitudes larger than 1.3. The data show two trends in the seismic activity rate
with a change point towards the end of 2012. This point coincides with the upgrading
of the monitoring system at the CGS. Therefore, it is safe to assume that the changes
are not associated with dynamic conditions in the rock mass of the Central Rand
Basin.
Figure 51: Cumulative number of earthquakes as a function of time, for the Central Rand Basin and with $M_w > 1.3$ from 10 June 2010 to 26 May 2015.

The analysis only focuses on the time interval from 1 November 2012 to 26 May 2015 (Figure 52). This period has a mean background rate of 1.02 events per day. The initial stage, which ends in the middle of June 2013, shows a significant drop in the rate of seismicity. In the next phase, for a period of several months, the rate systematically increases. During this time the seismicity is controlled by a large number of small events with one exception; on 18 November 2013, the largest seismic event with a magnitude $M_w$ 3.4 ($M_L$ 3.6) was recorded. After this event, the seismicity rate remained above the mean background rate. A few months later, a slowing of the seismicity rate is observed and from the beginning of 2015, the rate accelerates again, significantly. The above analysis indicates that stress changes are present in the Central Rand Basin.
Figure 52: Cumulative number of earthquakes as a function of time, for the Central Rand Basin and with $M_w > 1.3$ from 10 November 2012 to 26 May 2015;

The average rate of seismic deformation is $1.6 \times 10^{13}$ Nm/year. This is equivalent to a magnitude $M_w$ 2.7 event per year. The release of seismic deformation is not uniform. There are periods of low seismic activity, where sections of the curve for cumulative seismic moment are almost flat (Figure 53 (top)). The blue lines were obtained using a least squares polynomial fit. The rates of seismic moment release change significantly year on year. Over five consecutive years, the rate per year was as follows: $7.0 \times 10^{13}$ Nm/year (2010/2011), $1.0 \times 10^{13}$ Nm/year (2011/2012), $7.0 \times 10^{13}$ Nm/year (2012/2013), $0.4 \times 10^{13}$ Nm/year (2013/2014) and $0.9 \times 10^{13}$ Nm/year (2014/2015). A period of low seismic deformation follows a sudden release of seismic moments larger than $10^{14}$ Nm ($M_w > 3.2$). Usually, after a sudden release of large seismic moments, a period of almost a year of relative calmness follows, with an average rate of seismic moment of $0.006 \times 10^{14}$ Nm/year, which is equivalent to a single event of magnitude $M_w$ 1.8.
The average rate of radiated seismic energy is \(4.8 \times 10^7\) J/year (Figure 53 (bottom)). The curves of cumulative seismic moment and radiated seismic energy are similar, but there are some differences. The seismic moment associates with the seismic energy, therefore, a similar time evolution is observed for these parameters.

A constant seismic deformation is not observed during the last five years. The deviation from constant is in the order of \(6 \times 10^{13}\) Nm/year, which is a significant deviation. Similar conclusion was arrived at, during the first two years of observation (Cichowicz et al., 2012).
Figure 53: Temporal evolution of the cumulative seismic moment (top) and the radiated seismic energy (bottom) for the Central Rand Basin from March 2010 to May 2015. The blue lines were obtained using a least squares polynomial fit.

7.7.1.5 Investigation of properties of the inter-event time

The earthquake inter-event time, $T_i$, also called waiting time or recurrence time, is defined as the time between consecutive events: $T_i = t_i - t_{i-1}$ where $t_i$ is the time of occurrence of the $i$-th event. The temporal evolution of the inter-event time provides an understanding of the physical mechanisms of earthquake interaction. A change in the characteristics of the inter-event time occurs when a stress change is applied to a group of faults in a region that have been undergoing constant-rate tectonic loading. Alterations in the inter-event time reflect different tectonic loading rates.

In seismology, the initial hypothesis was that the inter-event time should follow a Poisson process. The Poisson process has an exponential distribution. The exponential density function is characterized by a constant seismicity rate parameter, which is defined as the number of events per unit time. The assumption that
earthquake occurrence follows a Poisson distribution means that the probability of event occurrence remains constant in time. A Poisson process in which earthquakes occur randomly does not account for time clustering of earthquakes. The Poisson process is memory-less and; therefore, unpredictable and not repeatable since the time of occurrence of the next event is unaffected by the time of occurrence of the previous one. Poisson may be applicable to large areas containing many tectonic faults.

The non-Poisson process has a probability density function which is not exponential. This type of process has a memory i.e. the current event remembers the occurrence of the last event. This process has a distribution that depends on the history of the process. Cornell and Winterstein (1988) have shown that the Poisson model is unsuitable when the seismic hazard is dominated by a single force and displays strong characteristics of time dependent behavior. Corral (2004, (a) and (b)) proposed a gamma distribution for the inter-event time to describe stationary seismicity (excluding aftershocks). The gamma distribution family is based on shape and scale parameters. The shape parameter, ‘a’, influences the peaked-ness of the distribution and the scale parameter, ‘b’, influences the spread distribution.

The histogram of the inter-event time is constructed for data from November 2012 to May 2015 for events above the magnitude of completeness (Figure 54(a)). The Poisson and gamma distributions are used to model the observed inter-event histogram. The temporal variation of the distribution parameters was investigated. The time series of the inter-event time was divided into three phases with each a duration of 12 months. The best fits of the Poisson and gamma distributions are displayed on top of the observed histograms (Figures 54 (b), (c) and (d)). The symbol, \( \mu \), marks the mean level of the seismicity rate. The two parameters of the gamma probability density function, pdf, are marked with the symbols \( \Gamma a \) and \( \Gamma b \).

Both distributions show a similar pattern for inter-event times larger than 6 days. The gamma distribution fits the observed data better than the exponential distribution over
the full range from 0.1 days to 9 days. In this broad range the gamma distribution fits well, while the exponential distribution does not follow the observation and is shifted to the right of the observed histograms. This indicates that the observed inter-event times are shorter than predicted by the exponential distribution.

![Figure 54](image)

Figure 54: (a) log-log plot of the inter-event time probability density function, pdf, for a period of 3 years from 1 Nov 2012 to 26 May 2015. The dark lines represent exponential and gamma distributions; (b) 12 months from 1 Nov 2012 to 1 Nov 2013; (c) 1 Nov 2013 to 1 Nov 2014; (d) 25 May 2014 26 May 2015

Results from this study indicate that fluid-induced sources have short inter-event times. Note that this behavior corresponds to a clustering of events, in which short recurrence times tend to be close to each other, forming clusters of events (Corra, 2006). Fluid-induced events do not appear randomly, as their observed density
distributions do not follow an exponential distribution function. The miss-fit of the empirical inter-event time to an exponential distribution indicates that the events triggered by fluid ingress have a high seismicity rate.

The shape parameter, $\Gamma_a$-value, of the gamma distribution does not change significantly for all the studied intervals of time. The variation in the shape parameter, $\Gamma_a$, is from 0.66 to 0.7 (Figure 54). The general characteristics of the gamma distribution point to systems of event clustering, i.e. if the $\Gamma_a$-value is lower than one then there is an enhanced probability of another event immediately following the previous one (relative to a Poisson process). Corral (2004 (a) and (b)) found that the density distribution of the inter-event time for global and local seismicity could be modelled with a gamma distribution where the $\Gamma_a$-value is equal 0.67.

7.7.2 Conclusions from Milestone 7

Characterization of the seismicity triggered by a rising water level in the Central Rand Basin is achieved through the estimation of source parameters. The relations between source parameters provide an understanding of the physical phenomena that occur in the medium as a result of flooding.

Static stress drop heavily influences ground motion characteristics, which, in urban areas, affects the risk assessment. The observed static stress drop varied from 0.05 MPa to 10 MPa. Large static stress drop is not only associated with large events. It was found, that large stress drops were sometimes associated with small as well as large events.

The static stress drop increases with an increase in the seismic moment for seismic moment values ranging from $10^{10}$ Nm to $10^{13}$ Nm. However, for a seismic moment larger than $10^{13}$ Nm, an upper limit for the static stress drop at 10 MPa was found.
The radiated seismic energy covers a range of approximately six orders of magnitude while scalar seismic moment varies by four orders. The variation of the apparent stress ranges from 0.01MPa to 1MPa.

The impact of the assumed attenuation models was investigated. The values of the scalar seismic moment and magnitude are not affected by the attenuation model, whereas static stress drop is.

Four events were identified for moment tensor inversion. Three of the four events display oblique strike-slip source mechanisms with the azimuth of the T axis in the North-East and the P axis in the North-West. One of the four events shows also strike-slip mechanism, but the azimuth of the T axis is in the North-West and that of the P axis is in the North-East. The events analyzed appear to have some non-shear components, because two of the events show implosional components, whilst the other two show tensile components. The implosional components may have two physical origins: (1) closure of faults due to radiated energy by preceding events, and (2) intersection of tensile faults with shear faults. However, the non-DC components may have been exaggerated by: (1) errors in the retrieval of the moment tensor due to noise and data limitations of the input data, (2) anisotropy in the focal area, and (3) inaccurate Green’s functions due to poor knowledge of the velocity model. The nodal planes as shown by the fault plane solutions are, in general, consistent with the observed fault structures that were observed in the now defunct mines of the Central Rand Goldfields.

A relationship between local and moment magnitude, $M_L$ and $M_w$, was derived. This relationship has important practical applications considering that magnitude provided by the CGS bulletin is $M_L$, while the mining networks use $M_w$.

The magnitude of completeness was established as $M_w = 1.3$ for the catalogue.
Trend analysis of the seismicity level can be used to establish the state of the seismic risk in the Central Rand Basin. The following conclusion is solid: The level of seismicity is not decreasing. On the contrary, there were several stages of increased seismicity over the five year period. The most convincing argument for this statement is that the number of strong events is still as high as it was when monitoring began. A study of the temporal variation of the spectral parameters in the Central Rand Basin showed that the scalar seismic moment was dominated by two earthquakes with values larger than $M_{0 Sv} = 10^{14} \text{Nm}$ and magnitudes larger than 3.

Tectonic loading or induced loading is responsible for stress perturbation and if applied to a fault population, produces a change in the seismicity rate. A correlation between changes in earthquake activity with stress has led to suggestions that stress changes could be calculated from earthquake occurrence rates. A mean background rate of 1.02 events per day was calculated. The average rate of seismic deformation was $1.6 \times 10^{13} \text{Nm/year}$. This is equivalent to one $M_w 2.7$ event per year. The release of seismic deformation was not uniform. There are periods of low seismic activity where sections of the cumulative seismic moment curves are approximately $0.06 \times 10^{13} \text{Nm/year}$. The deviation from the constant is in the order of $6 \times 10^{13} \text{Nm/year}$, which is a significant deviation. Cumulative sum charting shows that the mean value of the seismic system increases in the first half of 2015 in comparison with the mean over five years.

The temporal evolution of the event inter-event time provides an understudying of the physical mechanisms of earthquake interaction. A change in the characteristics of the inter-event time results when a stress change is applied to a group of faults in a region that have been undergoing a constant rate of loading. Results from this study indicate that the fluid-induced behaviour of the inter-event time corresponds to a clustering of events. Fluid-induced events do not appear at random, since the density distribution does not follow an exponential distribution function.
RECOMMENDATIONS FOR FURTHER RESEARCH

1. Analysis of the inter event time revealed that the seismicity occurs in clusters. This is a significant finding because it indicates that the Central Rand Basin experiences times of increased and decreased seismicity, periodically. This phenomenon should be investigated in detail as it has practical implications for a hazard assessment.

2. Temporal and spatial changes in the rock mass of the Central Rand Basin imposed by fluid related seismicity should be evaluated continuously for the next few years. Characterization of the dynamic processes in the rock mass is mainly obtained through estimating the values of the spectral parameters of the seismic source. The techniques used for trend analysis should be further developed to identify small deviations from the long term trend.

3. The prediction of ground motion caused by a maximum expected magnitude, which has not yet been observed, is a complex process, which requires validation using several tests. Therefore, testing of the parametric ground motion model should continue. Following this, the response spectra and other engineering parameters for the Orkney earthquake of magnitude 5.5 observed in KOSH area, should be calculated. The Orkney earthquake has a similar magnitude to the maximum expected magnitude for the Central Rand Basin area. Special attention should be given to an accurate estimation of the spectral parameters of the Orkney earthquake and the attenuation correction. Concurrently, a comparison between attenuation in the Central Rand Basin and the KOSH area should be conducted to find a suitable correction, making it possible to “import” an earthquake from KOSH to Central Rand Basin. The Orkney earthquake is the perfect candidate for such an exercise because of the shallowness of the event depth (3-4 km). Tectonic earthquakes usually occur much deeper.

4. Attenuation and amplification of high frequency signals caused by near surface geology strongly influences the values of seismic source spectral parameters.
Parameters, which control high frequency attenuation, i.e. kappa, must be estimated for all seismic stations to improve the estimations of seismic source parameters.

5. The damage curve for the Central Rand Basin should be recalculated to include data obtained from the Microzonation project sponsored by the Department of Mineral Resources. This project will produce a hazard map with site effects.

6. The strongest and potentially, most damaging ground motions, are observed at closest distances. Therefore, a detailed and systematic analysis of ground motion characteristics, when the seismic source is located close to the seismograph station, is required.

7. The faulting mechanism of the magnitude 5.5 Orkney earthquake was strike-slip, whereas in mining environments, normal faulting is expected. Strike-slip mechanisms are also observed in the Central Rand Basin. A suitable crustal stress model needs to be developed to better understand the observed faulting mechanisms.

**RECOMMENDATIONS FOR IMPLEMENTATION FOR THE SECTOR**

Implementation of the methodology described in the reports for interpretations of fluid induced seismicity using strong ground motion sensors installed on the surface.

The interpretations are based on accurate locations of seismic events in the Central Rand Basin area and advanced processing of waveforms. Key elements in processing the waveforms are estimations of the spectral parameters. Before spectral parameters can be extracted from a seismogram, a correction for path effect should be applied. Temporal and spatial changes in the rock mass imposed by fluid related seismicity should be evaluated continuously using a spectral analysis of the seismic
source. That includes the estimation of seismic moment, seismic energy, static stress drop and moment tensor.

Another key element of the methodology is the estimation of the maximum expected magnitude in the area and hazard maps with associated spectral acceleration. The initial parametric model for ground motion prediction was proposed and verified using available observations. The average amplification factor was obtained at a few selected points. The expected damage to urban structures typically found in the Johannesburg CBD due to seismicity was calculated.

Detailed geological information was made available through mining and this, ironically, formed the basis for mitigation in terms of stress modelling and the identification of possibly unstable structures in the Central Rand Basin. Locations of accurately mapped geological features in the mines should be used in conjunction with the locations of seismic events and an understanding of the stress state in the Central Rand Basin to establish the seismic hazard.

**TECHNOLOGY TRANSFER OPTIONS**

The methodology described in the reports should be implemented in all areas where fluid induced seismicity is observed and a seismograph network on the surface is available.

**CONCLUSIONS**

Major outcomes of the project are listed as follows:
• As a result of this project, we have a better understanding of the phenomena associated with fluid induced seismicity in the Central Rand Basin. Methodology to monitor this dynamic process was developed. The methodology utilizes spectral parameters of seismic sources and time series techniques.

• The level of seismicity in the Central Rand Basin is not showing signs of decreasing and is still as high as it was when monitoring began over five years ago.

• The total cumulative seismic moment released in the Central Rand Basin is lower than what was observed during mining. This could indicate that the rock mass is not yet in the equilibrium.

• The seismicity did not, for the most part, appear to migrate to areas outside of the old mining boundaries.

• An investigation into the tectonic stress conditions of the Central Rand Basin and geological structures that intersect the mines revealed possible seismically active structures. 3D modelling provided a means to identify unstable candidate faults.

• Analysis of the inter event time revealed that the seismicity occurs in clusters indicating that the Central Rand Basin experiences times of increased and decreased seismicity, periodically.

• The maximum expected magnitude in the Central Rand Basin was estimated.

• The initial parametric model for ground motion prediction was proposed and verified using available observations.

• The near surface site effect was obtained at few selected points. The average amplification factors for all sites varied between 1.5 and 3.3.
The expected damage to urban structures typically found in the Johannesburg CBD due to seismicity, was calculated. Based on the assessments, Johannesburg CBD, Germiston and Bedfordview are three suburbs with the highest potential exposure to seismic hazard and risk.

**REFERENCES**

**Milestone 2**


**Milestone 3**


**Milestone 4**


Milestone 5


**Milestone 6**


Cichowicz A., D. Birch, L. Labuschagne and G. van Aswegen (2013). Temporal and Spatial Variation of Seismicity and in the Central Rand Basin 2012 ENABLING OUTPUT 5 in project Fluid-Induced Seismicity in the Central Rand Basin Area: Ground Motion Prediction and the Development of an Early Warning System for Risk Reduction, Project number SIM11-02-01


**Milestone 7**


Corral A. 2006, Dependence of earthquake recurrence times and independence of magnitudes on seismicity history. Álvaro Corral. Departament de Física, Facultat de Ciències Tectonophysics 424 177-193


Nancy, C.H. Lo, 1994, Level of significance and power of two commonly used procedures for comparing mean values based on confidence intervals, CalCOFI Rep vol 35.


LIST OF APPENDICES

MILESTONE 4: Shallow crustal structure in the Central Rand Basin using local earthquakes and Multichannel Analysis of Surface Waves method
### FINANCIAL SUMMARY

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