CHAPTER 4

Earthquakes

CHAPTER 4: EARTHQUAKES

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Executive Summary

"Unconventional gas development" or "fracking" is a technology that uses high pressure fluid to create a network of fractures that extends for tens of meters from a borehole to provide pathways for the extraction of gas from low permeability rocks such as shale. The technology has greatly increased hydrocarbon production during the last decade, especially in the United States. It is believed that the Karoo Basin contains some shale strata that may contain significant resources of gas. The injection of fluids into the earth at pressures high enough and volumes great enough to cause rocks to fracture and/or faults to slip will inevitably cause seismic events. It is the purpose of this investigation to consider the potential risk posed by natural and induced seismicity in the study area, especially as many of the buildings in the Karoo, including heritage buildings, are considered to be vulnerable to shaking as they are built from adobe (mud brick) or unreinforced masonry.

Scenario 0: Reference Case

Southern Africa is a stable continental region with a low level of natural seismicity. Felt earthquakes (M>3) occur occasionally in the greater Karoo region, perhaps once or twice a year. Only two damaging events have been reported in the last century (Koffiefontein in the southern Free State, M_L6.2 in 1912; Tulbagh-Ceres in the Western Cape, M_L6.3 in 1969), both well outside the study area. Thus the occurrence of a felt earthquake within the study area is considered to be *unlikely*, and the occurrence of a damaging event to be *very unlikely*. The area is sparsely populated, apart from towns such as Beaufort West, Victoria West, Graaff-Reinet, Middelburg, Cradock and Queenstown. Most buildings, including important heritage buildings and dwellings, were built using unreinforced masonry and are thus vulnerable to damage and consequent injuries and loss of life similar to that experienced in the Tulbagh-Ceres district following the M_L6.3 earthquake in 1969 and in Khuma Township (near Orkney, North West Province) following the M_L5.5 earthquake in 2014. The first western style buildings were erected in this area around 1750 and the fact that some of these buildings have survived till today is testimony to the rarity of damaging earthquakes.

In summary, the occurrence of a damaging earthquake (say M>5) anywhere in the study area is considered to be *very unlikely*. The level of risk depends on the exposure of persons and vulnerable structures to the hazard. In the *rural parts* of the study area the exposure is *very low*, the consequences of an earthquake are likely to be *slight*, and hence the risk posed by earthquakes is considered to be *low*. While it is considered to be *very unlikely* that a damaging earthquake will occur within 20 km of a town, the consequences of such an event could be *moderate* or even *substantial*. Lives could be lost, and many buildings would need to be repaired. Hence the risk in urban areas is considered to be *moderate*.

Scenario 1: Exploration Only

Exploration activities do not involve the large scale injection of pressurised fluids. Trial injection tests will probably be carried out at a few wells. The triggering of a felt earthquake is considered to be *unlikely*, and the triggering of a damaging event to be *very unlikely*. Thus, *the risk posed by earthquakes in the study area* during the exploration and appraisal phase is considered to be *low* and not significantly different to the baseline.

Scenarios 2 and 3: Small and Big Gas

Should unconventional gas resources be developed in impermeable shale strata in the Karoo, fluid will be injected into boreholes at pressures that are high enough to cause the shale to fracture. This will cause numerous small seismic events. It is conceivable that the increase in pressure and the injection of fluids could induce slip on nearby faults and cause a felt earthquake.

Many thousands of hydraulic fracture wells have been drilled worldwide. Most only caused micro-seismic events ($M<3$) imperceptible to humans, while none of the few felt events have caused any damage (Ellsworth, 2013). To date, all damaging events associated with fluid injection are associated with the disposal of large volumes of waste water, not fracking. The disposal of waste water by injection into underground aquifers is forbidden by current South African legislation. Thus fracking is considered *very unlikely* to induce a damaging event. Providing fracking is not carried out within a distance of 20 km of a town, the consequences are considered to be *slight* and the risk *low*. The risk to persons and assets close to fracking operations in rural areas, such as workers, farm buildings and renewable energy and Square Kilometre Array (SKA) radio telescope infrastructure, should be handled on a case-by-case basis. Vulnerable structures should be reinforced and arrangements made to insure or compensate for damage. Should particularly attractive shale gas resources be found close to towns, it is essential to inform local authorities and inhabitants of any planned fracking activities and the attendant risks; enter into agreements to repair or compensate for any damage; monitor the induced seismicity; and slow or stop fracking if felt earthquakes are triggered.

It should be noted that the Earth's crust is heterogeneous and physical processes are complex. Rock properties and geodynamic stresses are not perfectly known, and the seismic history is incomplete. Thus we cannot categorically exclude the possibility that a large and damaging earthquake may be triggered by fracking. It is thus important that seismicity is monitored for several years prior to any fracking, and that a seismic hazard assessment is performed to provide a quantitative estimate of the expected ground motion. It is also conceivable that a felt natural event may occur while shale gas development (SGD) is in progress and be linked to it by the public and the media. Monitoring should continue during SGD to investigate any causal link between SGD and earthquakes. Should any such link be established, procedures governing fluid injection practice must be re-evaluated.

We recommend that Council for Geoscience's (CGS) seismic monitoring network be densified in the study area, and that vulnerability and damage surveys of buildings and other structures (e.g. bridges, dams) be carried out before, during and following any SGD activities. At the present time (August 2016) an additional six seismograph stations were being installed by the CGS. Other mitigation measures to be considered should include: monitoring of seismicity during SGD and the slowing or stopping of fracking if felt earthquakes are induced, schemes to guarantee compensation in the case of damage, disaster insurance, reinforcement of vulnerable buildings (especially farm and heritage buildings, schools and hospitals), enforcement of building regulations, training and equipping of emergency first responders, and earthquake drills in schools and work places.

CHAPTER 4: EARTHQUAKES

4.1 Introduction and scope

“Fracking” is a popular term for a technology that is used to extract gas from impermeable rocks such as shale at depths of several kilometres (km). Known technically as “unconventional gas development”, the technology uses high pressure fluid to create a network of fractures that extend for tens of meters from a borehole to provide pathways for the extraction of gas. The technology has greatly increased hydrocarbon production during the last decade, especially in the United States (US). It is believed that the Karoo Basin contains strata that may contain significant resources of shale gas.

MEASURING EARTHQUAKE SIZE AND EFFECTS

Magnitude (M) is a measure of the energy released by the earthquake and the dimensions and slip on the fault. Seismograms recorded by many widely-spread seismograph stations are integrated to assign a single magnitude to an event. The South African National Seismograph Network (SANSN) uses either the local magnitude scale (M_L) or the moment magnitude scale (M_w), which are essentially equivalent for M<6.5. The M_L scale uses the maximum amplitude of ground motion recorded at the various local stations, is quick and easy to measure, but saturates above M6.5. The M_w scale takes the entire seismogram into account and is derived from an assessment of the mass of rock moved (or work done, hence the subscript ‘w’) by the earthquake. M_w does not saturate and can be estimated from local, regional or global stations. It has been calibrated to match M_L for M<6.5.

Earthquakes are generally divided into the following categories: micro M<3, small 3<M<5, moderate 5<M<7 and major M>7. Natural earthquakes are generally only felt when M>3 and only cause damage when M>6. However, people unaccustomed to earthquakes may be frightened by the shaking that is produced by a M5 event, even though the amplitude of ground motion is 1/10 that of a M6 event. It should be noted that earthquakes induced by mining or fluid injection may cause damage if 5<M<6 because they occur at much shallower depths than natural events.

Intensity (I) describes the shaking experienced on the surface of the earth. Intensity generally decreases with distance from the epicentre (the point on the earth’s surface above the earthquake source), but is also affected by near-surface geology. Shaking is generally amplified where there is thick layer of alluvium. Reports by many widespread observers are collated to derive Intensity Data Points (IDPs) and compile an isoseismal map.

The SANSN uses the Modified Mercalli Intensity (MMI) Scale. An intensity of III indicates ground motion that is perceptible to people, especially on the upper floors of buildings; VI is felt by all, many people are frightened and run out of doors, and a few buildings may be slightly damaged; VIII causes slight damage to earthquake-resistant structures, considerable damage to solid buildings, and great damage to poorly-built buildings; while XII indicates total destruction, with objects thrown into the air.

The injection of fluids into the earth at pressures high and volumes great enough to cause rocks to fracture and/or faults to slip will cause seismic events and, very rarely, shaking of the ground that is felt on the surface. The key issue is their magnitude. The events may range in size from micro-seismic events ($M<3$) that are barely perceptible on the surface, to events that are large enough to alarm residents and cause damage to vulnerable structures, including heritage buildings or buildings built from adobe (mud brick) or unreinforced masonry, typical of the Karoo. It must be emphasised that the felt events ($M>3$) are almost always associated with the injection of massive volumes of waste water, and very rarely with the deliberate formation of fractures to liberate gas (i.e. fracking) (Ellsworth, 2013).

The only known study of the impact of fracking on South African seismicity was conducted under the auspices of the Water Research Commission (WRC) (Kijko and Smit, 2014). Kijko and Smit (2014) conclude that fracking *"can/will lead to high levels of seismic hazard in the parts of the Western Cape, the Free State, Gauteng, and towards the eastern border of the North West Province. Moderate hazard levels can be expected in the Limpopo Province and parts of the Northern Cape. The southern part of the Eastern Cape is subject to low levels of seismic hazard."*

The purpose of this study is to assess the earthquake risk posed by shale gas exploration and development in the study area in the central Karoo region, and advise how best any risk can be mitigated. In particular, the assumptions and conclusions of the WRC report on the effect on seismic hazard (Kijko and Smit, 2014) will be assessed. Mitigation measures to be considered include restrictions on the location and intensity of fracking activity, disaster insurance, reinforcement of vulnerable buildings, enforcement of building regulations, training and equipping of emergency first responders, and earthquake drills in schools and offices.

This chapter links most closely to the following chapters of the scientific assessment:

- Chapter 5: Water Resources (Hobbs et al., 2016)
- Chapter 6: Impacts on Waste Planning and Management (Oelofse et al., 2016)
- Chapter 12: Impacts on Human Health (Genthe et al., 2016)
- Chapter 15: Impacts on Heritage (Orton et al., 2016)
- Chapter 17: Electromagnetic Interference (Tiplady et al., 2016)
- Chapter 18: Impacts on Integrated Spatial and Infrastructure Planning (Van Huyssteen et al., 2016)

4.1.1 Overview of international experience

There is a large volume of published literature on the subject of shale gas development (SGD), fluid injection and seismicity. In some instances (e.g. in Oklahoma), earthquake activity increased dramatically in areas where fluid injection was implemented. Earthquakes with magnitudes as large as M5 were triggered and caused alarm and even damage to structures that are not resistant to shaking (e.g. unreinforced masonry, adobe). However, it must be noted that almost all cases where damaging earthquakes were associated with unconventional hydrocarbon production, the earthquakes are attributed to the injection of large volumes of waste water into deep aquifers, not to fracking (Ellsworth, 2013). It should also be noted that there are also cases where damaging earthquakes are associated with the large scale extraction of oil and gas, but without any fluid injection being practiced, for example, near Gröningen in the Netherlands (Amin, 2015).

The Governing Board of the National Research Council (US) commissioned a study to "examine the scale, scope, and consequences of seismicity induced during the injection of fluids related to energy production; to identify gaps in knowledge and research needed to advance the understanding of induced seismicity; to identify gaps in induced seismic hazard assessment methodologies and the research needed to close those gaps; and to assess options for interim steps toward best practices with regard to energy development and induced seismicity potential". The comprehensive 300 page report was published in 2013 (National Research Council, 2013). Their principal conclusions relevant to SGD in the Karoo are:

1. Seismic events caused by or likely related to energy development have been measured and felt in 12 American states. However, only a very small fraction of injection and extraction activities at hundreds of thousands of energy development sites in the US have induced seismicity at levels that are noticeable to the public.
2. The process of fracking as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events. Observations and monitoring of fracking treatments indicate that generally only micro-seismic events ($M<2$) are produced because the volume of fluid injected is relatively small and the area affected by the increase in pore pressure is generally small (Figure 4.1).
3. Injection for disposal of waste water into the sub-surface does pose some risk for induced seismicity, but very few events have been documented over the past several decades relative to the large number of disposal wells in operation.

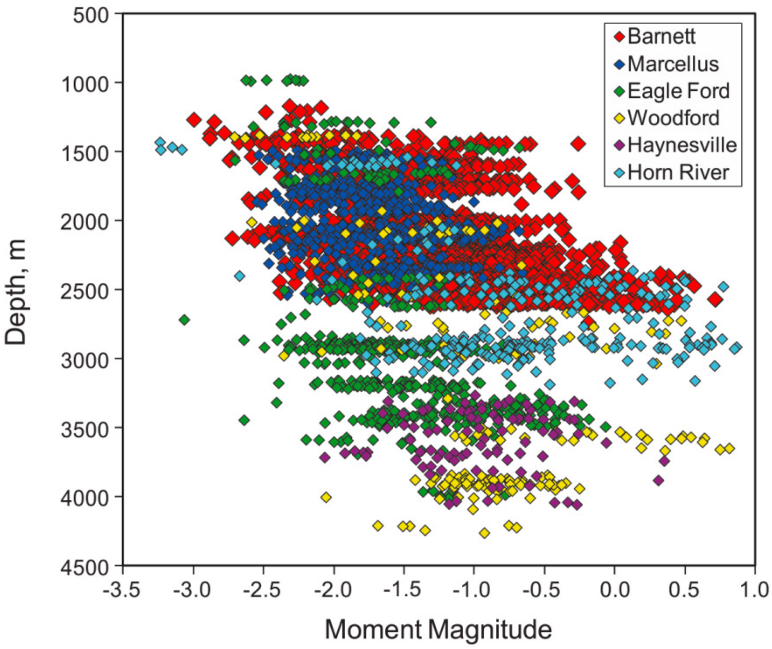

Figure 4.1: Maximum magnitude micro-earthquakes detected in six major unconventional reservoirs in the US. The micro-earthquakes are likely due to slippage along faults, natural fractures, and bedding planes, with the largest probably being fault interactions (Warpinski, 2013: 123).

Another important study was conducted by the Induced Seismicity Working Group (ISWG), a "collaborative effort of state oil and natural gas agency members and other advisory experts including industry and academia representatives to share science, research and practical experience that will equip the states with the best decision-making tools to evaluate the possible connections between seismic events and injection wells, minimise risk, and enhance appropriate readiness when seismic events occur". The ISWG published a 141 page report in 2015 (Groundwater Protection Council and Interstate Oil and Gas Compact Commission, 2015). The document focuses on seismicity induced by the underground disposal of fluids (e.g. brine) produced as a by-product of hydrocarbon extraction, as the potential for felt induced seismicity related to hydraulic fracturing was considered to be far lower than waste disposal. While fracking operations pump fluids into the well at higher rates and pressures than waste disposal wells, the procedure lasts only a short time (one to several hours) and the wellbore is fracked in stages (up to several hundred meters in length). Consequently, extended and prolonged contact with a fault is unlikely. Furthermore, the well may go into production soon after the fracking operation and thus becomes a pressure sink, drawing fluids into it and decreasing pore pressure in the vicinity of the well.

The ISWG report notes that very little ground motion data exists for the few reported incidences of seismicity associated with fracking, and no reports of damage. In the UK Bowland shale incident (De Pater & Baisch, 2011), at least one person apparently felt an M2.3 earthquake. In the Poland, Ohio, incident, some people felt the M3 earthquake and one of the smaller magnitude earthquakes. In the Horn River Basin (British Columbia Oil and Gas Commission, 2012) and the Montney trend incidents in Canada (Alberta Energy Regulator, 2015); numerous people onsite felt several earthquakes that were greater than M3.

Several moderate earthquakes (4<M<5) that occurred near Fox Creek in Alberta have been associated with fracking operations (Atkinson et al., 2016). In this case, the formations that were being fracked were close to crystalline basement. It is postulated that the increase in pressure triggered slip on pre-existing faults that extended into the basement. It should be noted that a rupture with an extent of the order of 1 km is required to produce a M4 earthquake. This is much greater than the length of fractures produced by fracking.

Several studies of seismicity induced by fluid injection have been published in prestigious refereed scientific journals in the last couple of years. For example:

- Kim (2013: 3506), in a paper in the *Journal of Geophysical Research*, reports that more than 100 small earthquakes (M_w0.4–3.9) were detected between January 2011 and February 2012 in the Youngstown, Ohio area. There were no known earthquakes in the past. The earthquakes were attributed to the disposal of waste water (brine) in Ohio produced by fracking carried out in Pennsylvania and transported to Ohio. The water was injected into deep wells at a depth range of 2.2–3.0 km under high pressure (up to 17.2 MPa).
- Walsh and Zoback (2015), in a paper published in *Science Advances*, show that the marked increases in the rate of small- to moderate-sized earthquakes in Oklahoma is associated with the injection of massive volumes of saline pore water that is coproduced with oil.
- McGarr (2014: 1008), in a paper published in the *Journal of Geophysical Research*, reports that the maximum magnitude of earthquake sequences induced by fluid injection at depth appears to be limited by the total volume of fluid injected. Similarly, the maximum seismic moment seems to have an upper bound proportional to the total volume of injected fluid (Figure 4.2). Fluid injection activities investigated by McGarr (2104: 1008) included (1) fracking of shale formations or coal seams to extract gas and oil, (2) disposal of waste water from gas and oil activities by injection into deep aquifers, and (3) the development of enhanced geothermal systems (EGS) by injecting water into hot, low-permeability rock. Of these three operations, waste water disposal is observed to be associated with the largest earthquakes, with magnitudes sometimes exceeding 5. McGarr (2014) reports that the micro-earthquakes (i.e. M<3) produced by permeability-enhancing treatments (i.e. fracking) are seldom large enough to be felt at the surface. He does, however, note that exceptions were reported by Holland (2013: 1784), De Pater & Baisch (2011), and the British Columbia Oil and Gas Commission (2012).

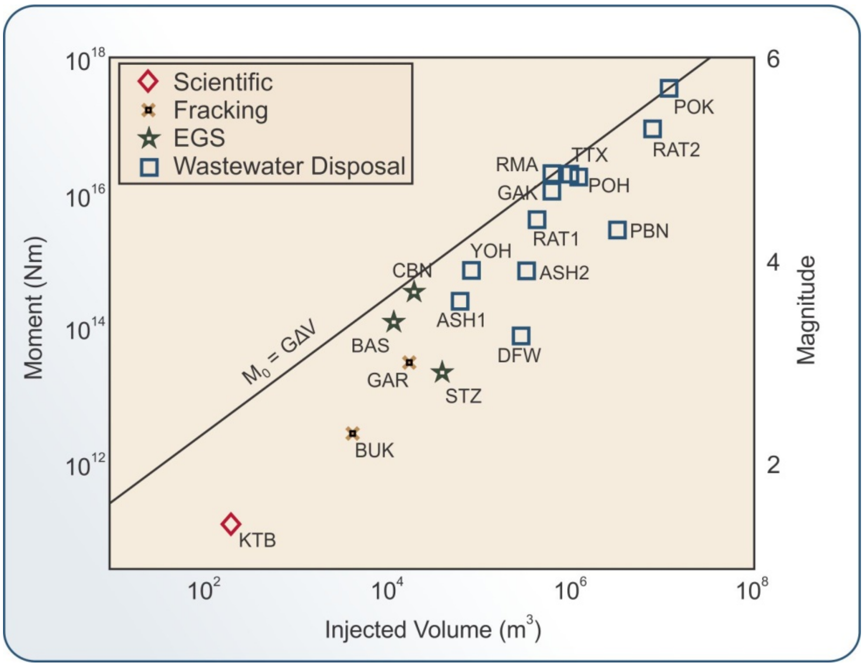

Figure 4.2: Maximum seismic moment and magnitude as functions of the total volume of injected fluid from the start of injection until the time of the largest induced earthquake. EGS denotes 'enhanced geothermal systems' (McGarr, 2014: 1008)

4.1.2 Earthquakes in the Karoo and environs

The South African Seismograph Network (SANSN) monitors local and regional seismicity (Figure 4.3). Southern Africa is, by global standards, a seismically quiet region as it is remote from the boundaries of tectonic plates. However, natural earthquakes do take place from time to time. They are driven by various tectonic forces, such as the spreading of the sea floor along the mid-Atlantic and mid-Indian ocean ridges, the propagation of the East African Rift System, and the response of the crust to erosion and uplift.

The Cape Fold Belt is seismically active. The largest instrumentally recorded earthquake was a M_L6.3 event that struck the Ceres-Tulbagh region on 29 September 1969, causing widespread damage and claiming 12 lives. It was felt as far away as Durban. Modern concrete-frame buildings sustained relatively minor damage, but some well-constructed brick houses were badly damaged and many adobe-type buildings were completely destroyed. The maximum MMI was VIII (Van Wyk & Kent, 1974). The Ceres-Tulbagh event provides a useful reference for the vulnerability of typical Karoo farmsteads and heritage buildings. On 12 January 1968 and 11 September 1969 events of magnitude M_L5.2 and M_L5.4 took place near Willowmore and Calitzdorp, respectively.

Another cluster of events north of the study area is found near Koffiefontein in the southern Free State. A M_L6.2 event that occurred on 20 February 1912 was felt over much of South Africa and assigned a maximum MMI of VIII (Brandt et al., 2005).

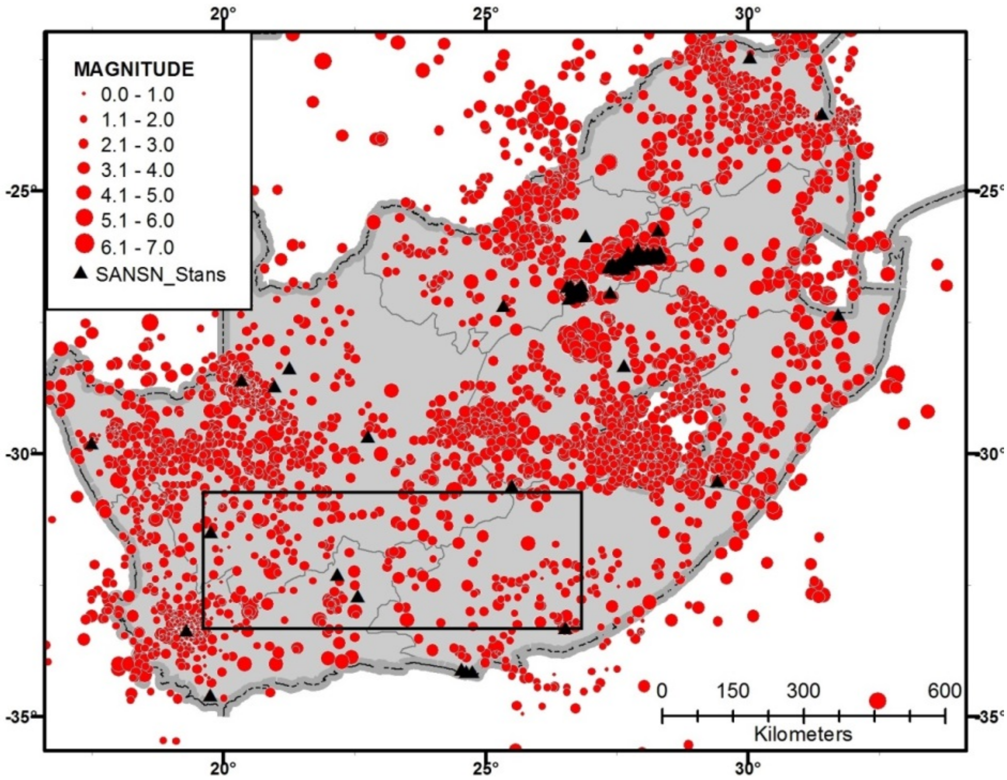

Figure 4.3: Location of recorded earthquakes in southern Africa. Black triangles indicate locations of SANSN stations; black rectangle indicates the study area. The period of data collection depicted is 7 January 1811 to 31 December 2014. (Source: Council for Geoscience, 2014).

Most seismic activity in South Africa is induced by deep level mining for gold and platinum. The largest event ever to occur in a mining region was the M_L5.5 event that struck Orkney on 5 August 2014, causing damage to numerous dwellings in nearby townships and one fatality. This event provides useful examples of the vulnerability of low-cost housing to strong ground motion.

In order to assess the risk posed by earthquakes, it is important to have a record of past earthquake activity. These parameters are best known if earthquakes are recorded by seismographs. However, the global instrumental catalogue does not go back much further than 1900, and, in many parts of the world, the recurrence time of the largest plausible earthquake is much longer than this. Thus historical records of earthquakes, while less accurate and complete, are a vital supplement to instrumental catalogues. However, the historical record in South Africa often only covers a few centuries and is inevitably incomplete. Thus palaeo-seismologists seek to extend the catalogue back in time by discovering and deciphering clues left by prehistoric earthquakes (say events occurring during the last 100 000 years). For example, geomorphological features such as fault scarps and knick points in rivers can be used to deduce the length and displacement of the rupture caused by a particular earthquake, while geochronological techniques can be used to determine the age of sediments deposited along fault scarps, and hence the minimum age of the earthquake.

Palaeo-seismic studies have been carried out as part of an investigation into the Quaternary tectonic history of the south-eastern continental margin, in support of the assessment of seismic hazard at proposed sites for nuclear power stations (Engelbrecht & Goedhart, 2009; Goedhart & Booth, 2009: 510; Midzi & Goedhart 2009). There is little seismic information for this region, and the record is too short to include the long recurrence intervals typical of large, surface-rupturing earthquakes in intraplate regions. Goedhart and Booth (2009: 510) interpreted a scarp running parallel to the Kango fault in the Cape Fold Belt to be the surface expression of an 84 km long extensional surface rupture. An 80 m long, 6 m deep and 2.5 m wide trench was dug across the fault, exposing 21 lithological units, six soil horizons, and 19 faults strands. Vertical displacement indicated a fault throw of about 2 m. Optically stimulated luminescence dating indicated that the fault was active between 12 200 and 8 800 years ago, and most probably around 10 600 years ago. Goedhart and Booth (2009: 510) used published relations between surface rupture length, displacement and magnitude to estimate the magnitude of the event at M_w7.4. It should be noted that there a fair degree of uncertainty associated with the magnitude assessment, as is the case with all palaeo-seismic investigations.

4.1.3 Relevant legislation, regulation and practice

The Minister of Mineral Resources published the “Regulations for Petroleum Exploration and Production. Notice R466” under Section 107 of the Mineral and Petroleum Resources Development Act (2002) in the Government Gazette dated 3 June 2015. [It should be noted that the validity of these regulations was being challenged in the High Court at the time of writing this report (August 2016) and they might be set aside.]

The regulations relevant to the risk posed by earthquakes induced by fracking include:

89. Assessment of related seismicity

(1) An applicant or holder must, prior to conducting hydraulic fracturing, assess the risk of potential fracking related seismicity and submit a risk assessment report and the proposed mitigation measures to the designated agency for approval and recommendation by the Council for Geoscience (CGS) and the risk assessment report must, as a minimum, identify -

> (a) stressed faults which must be avoided in the fracturing process;
>
> (b) fracture behaviour of targeted formations; and
>
> (c) the site-specific seismic monitoring to be undertaken pre-fracturing, during operation and post fracturing including the monitoring and reporting frequency.

(2) An applicant or holder must carry out site-specific surveys prior to fracking to characterise local stress regimes and identify proximal faults and the site characterisations must at least include-

(a) desktop studies of existing geological maps;

(b) seismic reflection and refraction data, where available;

(c) available background seismicity data;

(d) stress data from proximal boreholes where available; and

(e) other relevant available geophysical data, such as gravity.

(3) The risk assessment report contemplated in sub-regulation (1) and the site-specific surveys contemplated in sub -regulation (2) must be submitted to the competent authority, for consideration, as part of the application for Environmental Authorisation.

(4) The assessment of the orientation and slip tendency of faults and bedding planes may be done once faults have been identified and geological stress regimes characterised.

(5) The holder must mitigate risks of fault movement by identifying stressed faults by preventing fracturing fluids from entering stressed faults [sic].

(6) The holder must test fracture a targeted formation in a given well by using small pre-fracturing injection tests with micro-seismic monitoring.

(7) A holder must, following pre-fracturing injection tests contemplated in sub-regulation (6), investigate whether seismic activity occurs and then modify subsequent fracking operations.

(8) The holder must undertake seismic monitoring at the site for a period of 3 years after fracking activities have ceased and include the results of the seismic monitoring in the monitoring report contemplated in sub-regulation (1)(c).

112. Mechanical integrity tests and monitoring

(8) (a) During fracking, annulus pressure, injection pressure and the rate of injection must be continuously monitored and recorded.

(b) Micro-seismicity (in real time <5 minute delay) must be monitored by a long array of accelerometers located in an offset monitoring well, situated 100 m or more away from well at a comparable depth.

(c) Micro-seismic sensors must be designed for temperatures between 175-200 degrees Celsius.

(d) Tiltmeter measurements must be taken with an array of tiltmeters, either located in shallow offset wells (10 m) at the site surface or in a more sensitive deep offset well at comparable depth to fracking depth and in fracking well which provides info on fracture orientation and direction (azimuth).

120. Post fracking report

(1) A holder must compile and submit, to the designated agency and the department responsible for water affairs, a detailed post fracking operation report, for review and recommendations, which report must include among others-

(j) data and information concerning related seismic events, in internationally accepted formats, that have been recorded including the steps taken as a result of such events;

(k) plans to continue micro-seismic monitoring; and

(l) the induced seismic events that have been recorded including the steps taken as a result of such events.

124. General

(4) Disposal to underground, including the use of re-injection disposal wells, is prohibited.

132. Well decommissioning or closure

(1) A well that is no longer active, or producing, or for which the approved suspension period determined in terms of regulation 130 (b) has passed, must be plugged and decommissioned in accordance with-

(a) a decommissioning plan approved by the designated agency; and

(b) the relevant provision of the Environmental Impact Assessment Regulations.

(2) The decommissioning plan must take into account the following factors:

(j) related seismic activity risks.

These regulations provide a sound basis for discussions between regulators and developers of shale gas wells. Several of the clauses might require clarification, be too stringent, impractical or unnecessarily prescriptive. For example, the meaning of the phrase “fracture behaviour of targeted formations” (clause 89 (1) (b)) should be explained; while the stipulation that an array of accelerometers must be installed in a monitoring well (clause 112 (8) (b)) should be reviewed, as it is possible that satisfactory measurements could be obtained from a far cheaper surface array using modern location algorithms.

4.2 Key potential impacts and their mitigation

4.2.1 Unconventional shale gas development

Beginning in the 1960s, efforts were made to enhance oil recovery by injecting high pressure fluids into reservoirs to “hydrofracture” the rock. Sometimes the fluid was heated to reduce the viscosity of the oil. About the same time, technologies were developed to “steer” drilling bits so that targets could be reliably hit. The technology advanced to the extent that the trajectory of a hole could be deviated from the vertical to horizontal, enabling a far larger sub-surface area to be explored and exploited from a single drilling pad. Beginning in the 1990s, engineers in the US combined fracking and directional drilling to explore and exploit low permeability source rocks directly on a large scale. This required a great deal of technical development, including a variety of chemical additives to enhance the flow of oil and gas, and the introduction of sand grains to “prop open” the cracks. Generally, unconventional reservoirs are at depths of several kilometres. In the case of the Karoo Basin, the depth is likely to be in the range of 3 to 4 km.

4.2.2 Triggering of earthquakes by fluid injection

The injection of fluids into the rock at pressures that exceed its tensile strength will cause the intact rock to fracture, releasing some of the stored elastic energy as vibrations. During fracking, this is done in a controlled manner. The density and length of fractures is controlled by *in situ* conditions (such as the stress field), rock properties (such as the rock strength), and the fracking process (fluid pressure, density with which the well casing is perforated, and the length of borehole where the pressure is elevated). Generally, the desired length of fractures is of the order of tens of meters, while the length of borehole that is fractured (or “stimulated”) at any one time is, at most, a few hundred meters. Rock fracturing inevitably releases elastic energy stored in the intact rock. Generally the shaking is too weak to be felt on the surface.

Some researchers (e.g. McGarr et al., 2002: 647) draw a distinction between “induced” seismicity and “triggered” seismicity. Under this distinction, induced seismicity results from human-caused stress changes in the Earth’s crust that are on the same order as the ambient stress on a fault that causes slip. Triggered seismicity results from stress changes that are a small fraction of the ambient stress on a fault that causes slip. Anthropogenic processes cannot “induce” large and potentially damaging earthquakes, but anthropogenic processes could potentially “trigger” such events. Following the report of the National Research Council (2013), we do not distinguish between the two and use the term “induced seismicity” to cover both categories.

Earthquakes related to fracking are induced by at least three mechanisms:

(i) Cracking or rupturing of rocks in the vicinity of the wellbore that creates micro-earthquakes of very small magnitude, $M<0$;

(ii) Interaction between fracking fractures and nearby faults, where the fracking fluid enters the fault zone. This may causes a change in pore fluid pressure that can trigger earthquakes of $0<M<3$, and rarely, but possibly, greater.

(iii) Interaction between fracking fractures and nearby faults, through the transfer of stress through the rock. This may causes a change in the shear stress acting on the fault and trigger earthquakes of $0<M<3$, and rarely, but possibly, greater.

4.2.3 Damage caused by earthquakes

As noted above, natural earthquakes are rare in the study area, but cannot be entirely ruled out. The disposal of waste water into aquifers is forbidden in South Africa; thus the Oklahoma case of large fluid-induced earthquakes causing damage to surface structures will not occur. Fracking will cause micro-seismic events, but only a very few will be perceptible on the surface and the probability that they will cause any damage to surface structures is negligible. It is conceivable, although unlikely, that fracking might trigger slip on a pre-existing fault and cause an earthquake large enough to be felt. We cannot entirely rule out the possibility of damage and losses on the surface to:

(i) structures at fracking sites,
(ii) nearby farmsteads, villages and towns, and
(iii) nearby sensitive infrastructure (SKA radio telescopes).

However, to the best of our knowledge, no earthquake associated with fracking has caused damage to a surface structure anywhere in the world.

A significant part of damage observed from earthquakes is associated with the amplification of seismic waves due to local site effects. Local conditions can vary greatly due to variations in the thickness and properties of soil layers, which could have significant effects on the characteristics of earthquake ground motions on the ground surface to which buildings are subjected. Similar site effects are observed for structures built on hills, except the observed amplification is due to topographic effects.

Fracking and fracking-triggered earthquakes could cause damage and losses underground, even though the events might not be felt on the surface. For example:

(i) rupture of the well casing, should a slipping fault cut the casing, and
(ii) contamination of water resources, should there be interaction between aquifers, hydraulic fractures, faults and leaking casings.

As noted by Hobbs et al. (2016), there are no documented and verified cases of contamination of potable groundwater resources from the fracking process itself. Surface spills or faulty casing and poor well maintenance account for all proven contamination.

4.2.4 Mitigation of impacts

Several practical steps should be taken to mitigate earthquake risk in the region.

- Monitor seismicity before, during and after fracking. Ideally, monitoring of earthquakes should start at least 1 to 2 years before fracking (at a minimum to obtain base line seismic activity in area) and for about 3 years after fracking ends to investigate effect of fluids flowing through fractures and faults. Using the seismograph stations of the SANSN, the CGS has built a database of earthquake locations, which can form the basic baseline data for the study area (Figure 4.3). It shows that moderately sized earthquakes (M>4) have previously occurred in the region, prompting serious consideration and planning for the mitigation of earthquake effects in the region.

- Identify faults by mapping regional and local structures in the field, in boreholes and with geophysical methods.
- Measure the regional stress (e.g. from proximal boreholes) to characterise regional and local stress regime.
- Analyse seismicity data (location, source parameters) as well as stress data to identify pre-stressed and active/capable faults. Improved monitoring at regional level can assist in identifying active fault structures.
- Obtain orientations and slip tendency of identified active/capable faults.
- Mitigate risks of fault movement by preventing fluids from flowing into pre-stressed faults by informed location of fracking wells.
- Perform real-time micro-seismic monitoring during appraisal and production.
- Implement “traffic light” systems (i.e. feedback system) during fracking that will enable operators to respond quickly to induced earthquakes by either reducing the rate of fracking or stopping fracking altogether (Majer et al., 2007: 185).
- Assess seismic hazard and risk to determine (i) the expected maximum magnitude of earthquakes, and (ii) the expected maximum ground motion at the fracking site and in the region. Assessments should be conducted before (baseline), during and after fracking. The impact on ground motion at nearby towns and facilities (e.g. the SKA) should be considered.
- Assess the regional strain field through analysis of data recorded by the national geodetic network.
- Assess the building typologies in the region.
- Inspect buildings and structures prior to fracking to assess their condition.
- Reinforce vulnerable buildings and structures. Some simple measures may reduce the severity of earthquake damage. For example, buttress walls, strapping of hot water heaters (geysers) to rafters, stabilisation of towers carrying water tanks with anchor cables.
- Enforce building codes.

4.2.5 Cumulative impacts

Here we consider an extreme scenario where large scale SGD (Big Gas scenario) is accompanied by urbanisation and other industrial developments such as uranium mining and renewable energy projects. These developments will not have any effect on the seismic hazard (i.e. the likelihood of earthquakes occurring), but could affect the risk as more assets and people will be exposed to harm. We believe that it is possible to mitigate the risk posed by fracking-triggered earthquakes by ensuring that all new structures are built using modern materials and techniques to that they are able to withstand moderate intensities of shaking. Regardless of fracking, this would be a sensible precaution as a moderate natural earthquake will occasionally occur somewhere in the Karoo.

4.3 Risk assessment

4.3.1 How seismic hazard and risk is measured

Hazard assessment is the process of determining the likelihood that a given event will take place. Probabilistic seismic hazard assessment (PSHA) is generally expressed in terms of the ground motion (for example, peak ground acceleration (PGA)) that has a certain likelihood of exceedance (say 10%) in a given period (say 50 years). There are many PSHA schemes, but all require a catalogue of earthquakes (size, time, location); the characterisation of seismically active faults and areas (usually in terms of the maximum credible magnitude and recurrence periods); and a prediction of variation in ground motion with distance from the epicentre. The longer the duration of the catalogue, the smaller the magnitude of completeness, and the better the zonation, the more reliable is the PSHA.

The consequences of an earthquake depend on four main factors: the vulnerability of buildings to damage, the exposure of persons and other assets to harm, the cost of reconstruction, and the cost of lost economic production. Risk assessments are useful for raising awareness of possible disasters and motivating policies and actions to mitigate losses and avoid disasters. For example, vulnerable buildings may be reinforced, building codes enforced and insurance taken out to cover possible losses.

The moment there is human interference (i.e. fluid injection); probabilistic hazard assessment techniques cannot be used. The most reliable approach is to consider analogous situations elsewhere in the world.

Scenario 0: Reference Case

In the absence of shale gas exploration, natural events will occur from time to time. The important parameters are the maximum magnitude (M_{max}), the recurrence interval, and the likely ground motion.

These parameters are difficult to determine in a region where the seismicity is low, the instrumental catalogue is of short duration, and there are no recordings of strong ground motion.

The largest instrumentally recorded events in the region have magnitudes of M_L6.2 (Koffiefontein, 1912) and M_L6.3 (Ceres, 29 September 1969). In the absence of a lengthy and complete catalogue, it is standard practice to assume that the maximum credible magnitude is 0.5 units larger than the maximum observed event. Palaeo-seismic studies suggest that a M_w7.3 event occurred along the Kango Fault some 10 000 years ago.

The most recent published probabilistic hazard assessment is by Fernández and du Plessis (1992). They found that the PGA with a 10% probability of being exceeded in 50 years is less than 0.05 g in the study area, rising to a value greater than 0.2 g in the Ceres region. The CGS is in the process of developing new seismic hazard maps of South Africa (Midzi et al., 2016).

Based on these studies, the occurrence of a felt earthquake within the study area is considered to be *unlikely*, and the occurrence of damaging event to be *very unlikely*. The area is sparsely populated, apart from the towns such as Beaufort West, Victoria West, Middelburg, Queenstown, Cradock and Graaff-Reinet. Hence the *exposure is generally low* and the consequences of an earthquake are generally considered to be *slight*. However, very few buildings in the region were constructed to withstand strong shaking. Most buildings, including important heritage buildings and dwellings, were built using unreinforced masonry and are thus *vulnerable* to damage similar to that experienced in the Ceres-Tulbagh region in 1969 and in Khuma Township near Orkney in 2014. Thus the consequences of a shallow M>5 earthquake occurring within 20 km of a town could be *moderate* or even *substantial*. Considering the *very low likelihood of the occurrence* of a damaging earthquake and *low exposure*, the *risk* posed by earthquakes in the study area is thus considered to be *low*.

Scenario 1: Exploration Only

Exploration activities do not involve the large scale injection of pressurised fluids. Trial injection tests may be carried out at a few wells. The triggering of a felt earthquake is considered to be *unlikely*, and the triggering of a damaging event to be *very unlikely*. Thus, the risk posed by earthquakes in the study area during the exploration phase is considered to be *low* and not significantly different from the base line.

Scenarios 2 & 3: Small and Big Gas development

Should unconventional gas resources be developed in impermeable shale strata in the Karoo, fluid will be injected into boreholes at pressures that are high enough to cause the shale to fracture, thereby creating a network of pathways that enables the gas to be extracted.

In the case of limited production of a small resource (Small Gas scenario), there is likely to be localised induced seismicity, depending on the location of fracking wells in relation to faults in the region and at fracking site. It is *unlikely* that the seismicity will be felt on the surface, and *very unlikely* that it will cause any damage.

In the case of large scale production of a rich resource (Big Gas scenario), there is likely to be an increase in the frequency of felt earthquakes in the vicinity of the production wells. The likelihood of induced seismicity depends on the location of wells in relation to faults (especially faults that are close to instability) and the rate of fracking.

Many thousands of hydraulic fracture wells have been drilled worldwide. Most only caused micro-seismic events (M<3) imperceptible to humans, while none of the few felt events have caused damage. To date, all damaging events associated with fluid injection are associated with the disposal of large volumes of waste water. The disposal of waste water by injection into underground aquifers is forbidden by current South African legislation. Thus fracking is considered *very unlikely* to induce a damaging event. However, we cannot entirely exclude the possibility that a shallow M>5 event will be induced.

The damage produced by mining-related event that struck the Orkney area in the North West Province on 5 August 2014 damaging more than 600 dwellings (mostly constructed of unreinforced masonry) provides a local example of the relationship between the distance from the epicentre, the intensity of shaking and vulnerability of structures (Midzi et al., 2015). The highest intensity value obtained was VII, which was experienced at Khuma, Orkney, Stilfontein, Klerksdorp, Vaal Reef Mine and Buffelsfontein, all within 20 km of the epicentre. While acknowledging that there is a large variability in the intensity of ground motion, we have used this number as the basis for differentiating the risk posed by a shallow earthquake (<5 km depth) within 20 km of a town and that posed by a more distant earthquake.

4.3.2 Earthquake risk matrix

In order to illustrate the risk posed by earthquakes in the study area, we considered a worst case scenario, using the Ceres-Tulbagh earthquake of 29 September 1969 and the Orkney earthquake of 5 August 2014 as credible examples of natural and induced earthquakes, respectively. Should a M>6 natural earthquake or a shallow M>5 induced earthquake occur within 20 km of Graaff-Reinet, dozens or even hundreds of heritage buildings and dwellings could be damaged, some severely. Dozens of people could lose their lives. Repair costs could average perhaps 20% - 40% of the cost of the building stock, amounting to hundreds of millions of Rand, and the consequence would then be judged *moderate* to *substantial*. However, the likelihood of a natural event occurring is considered to be *very unlikely*, and the risk posed by this scenario is considered to be *low,* or at most *moderate.* Based on international experience, fracking is *highly unlikely* to induce a M>5 earthquake, but this cannot be entirely excluded, and the consequences could be *moderate* or even *substantial*. The implementation of mitigating measures would decrease the likelihood and consequences to some extent, although this is difficult to quantify (Table 4.1).

It should be noted that the Earth's crust is heterogeneous and physical processes are complex. Thus we cannot categorically exclude the possibility that a large and damaging earthquake may be triggered by fracking. It is also conceivable that a felt natural event may occur while SGD is in progress and be linked to fracking operations by the public and the media. It is thus important that seismicity is monitored for several years prior to any fracking and during SGD (say threshold of completeness M1, and with stations sufficiently dense to determine the depth of the hypocentre) to investigate any causal link between SGD and earthquakes. Should any such link be established, procedures governing fluid injection practice must be re-evaluated.

The question arises as to the limits of acceptable change with regard to ground shaking. It is well known that humans can perceive ground vibration at levels as low as 0.8 mm/s, much lower than the level of vibration that will damage even the most fragile structures (about 6 mm/s). Daily life in a family home will produce perceptible vibrations, for example: walking = 1 mm/s, jumping = 7 mm/s, and slamming the door = 12 mm/s (Scott, 1996). Experience gained from open pit mining shows that the main reason for complaints about ground vibration is not usually structural (or even cosmetic) damage, but the fear of damage and/or nuisance. Good public relations and explanations will help to reduce anxiety and complaints.

Table 4.1: Earthquake risk matrix

			Without mitigation			*With specified mitigation*		
Impact	**Scenario**	**Location**	**Consequence**	**Likelihood**	**Risk**	**Consequence**	**Likelihood**	**Risk**
Damaging earthquakes induced by fracking.	Reference Case	Wells within 20 km of towns	Slight	Very unlikely	Low	Slight	Very unlikely	Low
	Exploration Only		Slight	Very unlikely	Low	Slight	Very unlikely	Low
	Small Gas		Slight	Not likely	Low	Slight	Not likely	Low
	Big Gas		Moderate	Not likely	Moderate	Moderate	Not likely	Moderate
	Reference Case	Wells beyond 20 km of towns	Slight	Very unlikely	Low	Slight	Very unlikely	Low
	Exploration Only		Slight	Very unlikely	Low	Slight	Very unlikely	Low
	Small Gas		Slight	Very unlikely	Low	Slight	Very unlikely	Low
	Big Gas		Slight	Unlikely	Low	Slight	Not likely	Low

Figure 4.4 presents a risk map of damaging earthquakes across four SGD scenarios, with- and without mitigation.

4.3.3 Previous assessments of seismic hazard owing to fracking

The only known previous study of the impact of fracking on South African seismicity was conducted under the auspices of the WRC (Kijko and Smit, 2014). The report is entitled *"Possible Effect of Hydraulic Fracturing on Seismic Hazard in South Africa"*. Kijko and Smit (2014) conclude that fracking *"can/will lead to high levels of seismic hazard in the parts of the Western Cape, the Free State, Gauteng and towards the eastern border of the North West Province. Moderate hazard levels can be expected in the Limpopo Province and parts of the Northern Cape. The southern part of the Eastern Cape is subject to low levels of seismic hazard."*

It is clear that our conclusions differ significantly from those of Kijko and Smit (2014). We seek to explain why this is so.

- Kijko and Smit (2014) consider the entire region of South Africa, while our study is focused on the study area in the Karoo. The baseline hazard in study area is low compared to other parts of South Africa.
- Kijko and Smit (2014) use a methodology where they use a current probabilistic hazard assessment as a starting point, and then compute the increase in hazard should seismic activity increase by factors of 2, 5 and 10; as well as an assessment that combines the Reference Case and the three scenarios, assigning weights of 0.15, 0.50, 0.30 and 0.05 to each scenario, respectively. Kijko and Smit (2014) "strongly emphasise that the weights are very subjective; it was selected according to a wide scatter and often contradicting expert opinions on the effect of hydraulic fracturing on seismicity".

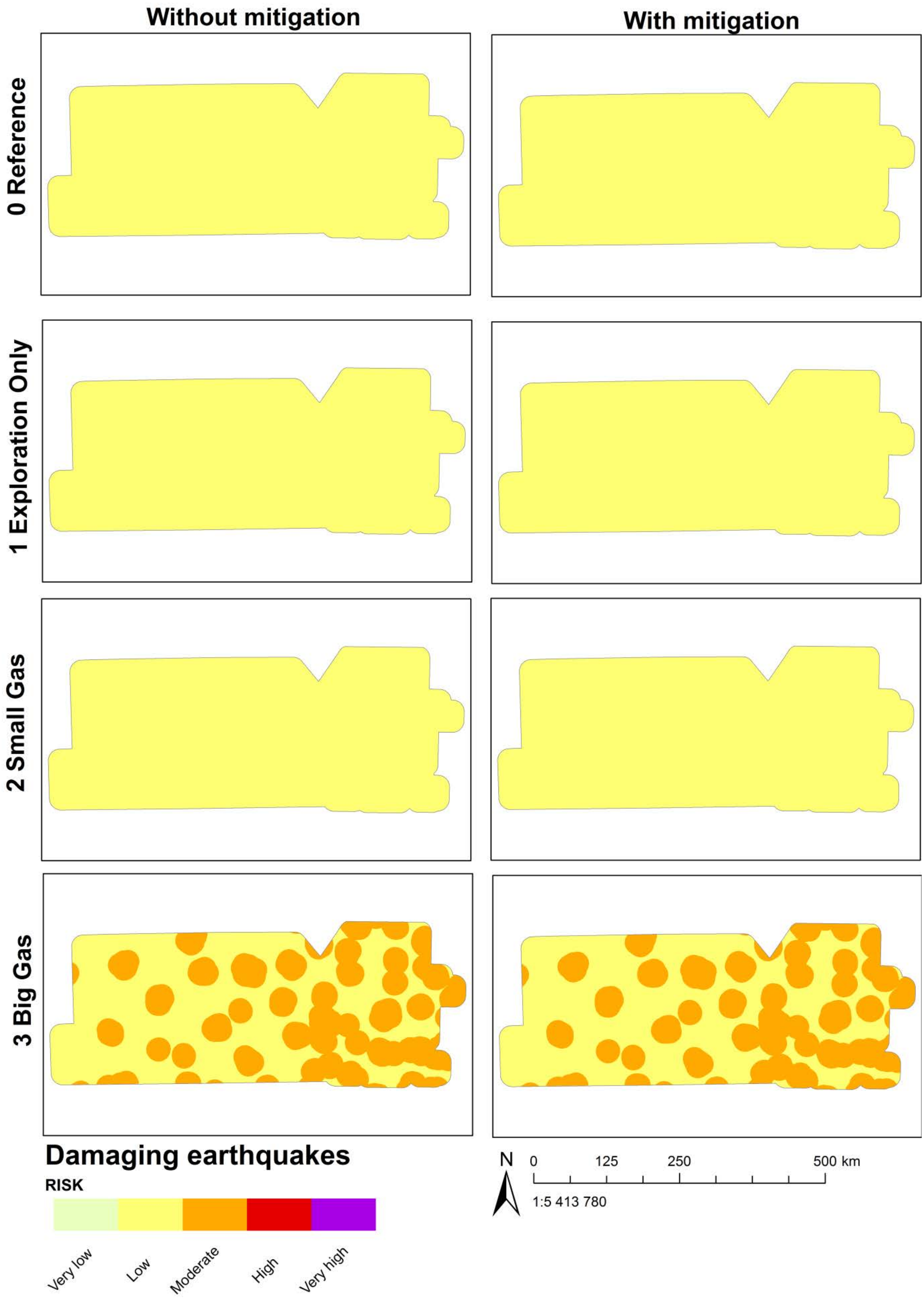

Figure 4.4: Map indicating the risk of damaging earthquakes across four SGD scenarios, with- and without mitigation.

- It is our opinion that the approach used by Kijko and Smit (2014) overstates the increase in hazard. International experience based on hundreds of thousands of fracking stimulations worldwide, indicates:
    - Seismicity induced by fracking is transient (hours to days), limited to the immediate area surrounding the wellbore (hectares to perhaps a square kilometre), and have magnitudes that are proportional to the volume of fluid that is injected. Natural seismicity is driven by tectonic forces that operate on geological time scales on crustal blocks and faults with dimensions of tens to hundreds of kilometres.
    - The vast majority of seismic events induced by hydraulic fracturing have $M<0$. Only a very small fraction have $M>3$ and are felt on the surface. No events have been reported to exceed M5. Thus the frequency-magnitude distribution of seismic events induced by fracking differs greatly from the frequency-magnitude distribution of natural seismic events.

4.4 Best practice guidelines and monitoring requirements

The regulations gazetted by the Minister of Mineral Resources on 3 June 2015 provide sound guidelines for best practice and monitoring, although, as noted above, there are some aspects that might require clarification, be unnecessarily stringent or prescriptive. It should also be noted that, at the present time (August 2016), the validity of the regulations were the subject of a High Court challenge.

Other mitigation measures to be considered should include:

- Establishment of ‘buffer zones’ around towns (say 20 km in radius) where fracking operations are either prohibited or carried out under strict control e.g. the rate of fracking controlled to limit felt seismicity,
- Reinforcement of vulnerable buildings (especially farm buildings, heritage buildings, schools and hospitals),
- Guarantees of compensation for any damage caused by fracking-induced earthquakes,
- Enforcement of building regulations,
- Disaster insurance,
- Training and equipping of emergency first responders, and
- Earthquake drills in schools and offices (drop, cover, hold on!).

We recommend that the SANSN, operated by the CGS, be densified in the study area, and that surveys of buildings and other structures (e.g. bridges, dams) be carried out before, during and following any SGD activities. The CGS currently operates only two seismograph stations within the study area, and another four stations close to its perimeter (see Figure 4.3). It is desirable that sufficient stations are installed so that all events exceeding M1 are recorded in any part of the area where SGD is likely to take place. These areas will only become apparent when the exploration and appraisal phase nears completion. At the present time (August 2016) a further six stations were being installed by the CGS in the study area. This should improve the threshold of completeness to M1 (Midzi, pers comm.)

The monitoring of seismicity at the well site is normally the responsibility of the license holder. The seismic network designed for monitoring background seismicity should calculate longitude, latitude and depth of small events (say threshold of completeness M1.0). The depth of small events has to be accurately determined in order to understand the dynamical processes that are taking place in the area of future fracking. The accuracy of location should be of the order of 100 m. The seismic arrays should be designed accordingly and advanced location algorithms used. Routine processing of seismic data should include an estimation of spectral parameters such as scalar seismic moment, seismic energy, and static stress drop, which will help to identify a stressed fault as is required by clause 89(1)(b) of the regulations (see Section 3.1.3: Relevant legislation, regulation and practice).

4.5 Gaps in knowledge

The principal lack of information with regard to the assessment of the risk posed by earthquakes is the lack of baseline information on the regional stress field, seismicity and active faults. It is clear from available information (Figure 4.3) that there is seismic activity in the region. However, given the sparse seismograph station distribution in the country, especially in the study area in the Karoo, the available data is not adequate to identify and characterise the active structure. Improved monitoring by densifying the network would certainly assist. Detailed geological and geophysical studies of identified structures would also be necessary.

4.6 References

Alberta Energy Regulator. 2015. Observed Seismicity and Oil and Gas Operations: Operators' Responsibilities. Available: http://www.aer.ca/rules-and-regulations/bulletins/bulletin-2015-03 [2016, May 31]

Amin, L. 2015. Shell and Exxon's €5bn problem: gas drilling that sets off earthquakes and wrecks homes. Available: https://www.theguardian.com/environment/2015/oct/10/shell-exxon-gas-drilling-sets-off-earthquakes-wrecks-homes [2016, August 23].

Atkinson, G.M., Eaton, D.W., Ghofrani, H., Walker, D., Cheadle, B., Schultz, R., Shcherbakov, R., Tiampo, K., Gu, J., Harrington, R.M. & Liu, Y. 2016. Hydraulic fracturing and seismicity in the Western Canada Sedimentary Basin. *Seismological Research Letters*, *87*(3), 631-647.

Brandt M. B. C., Bejaichund M., Kgaswane E. M., Hattingh E. & Roblin D. L. 2005. *Seismic history of southern Africa*. Seismological Series 37. Pretoria, South Africa: Council for Geoscience.

British Columbia Oil and Gas Commission. 2012. Investigation of Observed Seismicity in the Horn River Basin. Available: https://www.bcogc.ca/node/8046/download [2016, May 31]

De Pater, C. J. and Baisch, S. 2011. Geomechanical Study of Bowland Shale Seismicity. Cuadrilla News. Available: http://www.cuadrillaresources.com/news/cuadrilla-news/article/geomechanical-study-of-bowland-shale-seismicity/ [2016, May 31]

Ellsworth, W. L. 2013. Injection-induced earthquakes. *Science 341*(6142), 1225942, DOI: 10.1126/science.1225942

Engelbrecht, J & Goedhart, M. L. 2009. Advanced differential interferometry for detection of crustal warping and potential movement along the Baviaanskloof Fault – towards earthquake hazard assessment. *Abstract and poster. General Assembly of the International Association of Seismology and Physics of the Earth's Interior (IASPEI)*, 12-16 January 2009, Cape Town, South Africa.

Fernández, L. M. & du Plessis, A. 1992. *Seismic hazard maps of southern Africa*. Pretoria, South Africa: Geological Survey of South Africa.

Genthe, B., Maherry, A., Steyn, M., Rother, A., London, L., and Willems, M. 2016. Impacts on Human Health. In Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L. and de Jager, M. (eds.). 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks, CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7

Goedhart, M. L. & Booth, P. W. K. 2009. Early Holocene extensional tectonics in the South-eastern Cape Fold Belt, South Africa. Short paper. *Proceedings of the 11th Technical Meeting of the South African Geophysical Association*, 16-18 September 2009, Ezulwini, Swaziland. 510-513.

Groundwater Protection Council and Interstate Oil and Gas Compact Commission, 2015. *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation.* Available: http://www.gwpc.org/sites/default/files/finalprimerweb.pdf [2016, May 31]

Hobbs, P., Day, E., Rosewarne, P., Esterhuyse, S., Schulze, R., Day, J., Ewart-Smith, J., Kemp, M., Rivers-Moore, N., Coetzee, H., Hohne, D., Maherry, A. and Mosetsho, M. 2016. Water Resources. In Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L. and de Jager, M. (eds.). 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks, CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7

Holland, A. 2013. Earthquakes triggered by hydraulic fracturing in south-central Oklahoma. *Bulletin of the Seismological Society of America*, *103*(3). 1784–1792.

Kijko, A. & Smit, A. 2014. *Possible Effect of Hydraulic Fracturing on Seismic Hazard in South Africa*. (Report No. K5/2149), Pretoria, South Africa: Water Research Commission Project.

Kim, W. Y. 2013. Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. *Journal of Geophysical Research: Solid Earth*. *118*(7). 3506-3518.

Majer, E. L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B. & Asanuma, H. 2007. Induced seismicity associated with Enhanced Geothermal Systems, *Geothermics*, *36*(3), 185-222.

McGarr, A. 2014. Maximum magnitude earthquakes induced by fluid injection. *Journal of Geophysical Research: Solid Earth*, *119*(2), 1008-1019.

McGarr, A., Simpson, D. & Seeber, L. 2002. Case histories of induced and triggered seismicity. In *International Handbook of Earthquake and Engineering Seismology*, *Part A*, W.H.K. Lee *et al*. Eds., New York: Academic Press. 647-661.

Midzi V. & Goedhart M. L. 2009. Paleoseismic investigation along the Kango Fault, South Africa: determination of associated uncertainty. Abstract and poster. *30th General Assembly of the International Association of Seismology and Physics of the Earth's Interior (IASPEI)*. 10-16 January 2009. Cape Town, South Africa.

Midzi, V., Mulabisana, T., Manzunzu, B., Zulu, B., Pule, T., Myendeki, S. & Rathod, G. 2016. Seismic Hazard Assessment of South Africa: Seismic Source Characterisation. *AfricaArray Scientific Workshop*. 18-19 January 2016. Johannesburg, South Africa: University of the Witwatersrand.

Midzi, V., Zulu, B., Manzunzu, B., Mulabisana, T., Pule, T., Myendeki, S. & Gubela, W.,2015. Macroseismic survey of the M_L5. 5, 2014 Orkney earthquake. *Journal of Seismology*, *19*(3), 741-751.

National Research Council. 2013. *Induced Seismicity Potential in Energy Technologies.* New York, USA: National Academies Press.

Oelofse, S., Schoonraad, J. and Baldwin, D. 2016. Impacts on Waste Planning and Management. In Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L. and de Jager, M. (eds.). 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks, CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7

Orton, J., Almond, J., Clarke, N., Fisher, R., Hall, S., Kramer, P., Malan, A., Maguire, J. and Jansen, L. 2016. Impacts on Heritage. In Scholes, R., Lochner, P., Schreiner, G., Snyman-van der Walt, L. and de Jager, M. (eds.). 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks, CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7

Scott, A. Ed. 1996. *Open Pit Blast Design: analysis and optimisation.* Brisbane, Australia: Julius Kruttschnitt Mineral Research Centre.

Tiplady, A., van der Merwe, P. and Otto, B. 2016. Electromagnetic Interference. In Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L. and de Jager, M. (eds.). 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks, CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7

Van Huyssteen, E., Green, C., Paige-Green, P., Oranje, M., Berrisford, S., McKelly, D. 2016. Impacts on Integrated Spatial and Infrastructure Planning. In Scholes, R., Lochner, P., Schreiner, G., Snyman-Van der Walt, L. and de Jager, M. (eds.). 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks, CSIR/IU/021MH/EXP/2016/003/A, ISBN 978-0-7988-5631-7

Van Wyk W. L. & Kent L. E. (Eds). 1974. *The earthquake of 29 September 1969 in the southwestern Cape Province, South Africa*. Seismologic Series 4. Pretoria, South Africa: Geological Survey of South Africa.

Warpinski, N. R., 2013. Understanding hydraulic fracture growth, effectiveness, and safety through microseismic monitoring. In *ISRM International Conference for Effective and Sustainable Hydraulic Fracturing*. 20 May 2013. International Society for Rock Mechanics. 123-135. Available: http://cdn.intechopen.com/pdfs-wm/44586.pdf [2016, May 31]

Walsh F. R. & Zoback M. D. 2015. Oklahoma's recent earthquakes and saltwater disposal. *Science Advances, 1*(5), e1500195.