CHAPTER 4:
EARTHQUAKES

Second Order Draft for Stakeholder Comment

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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 in 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 study to investigate the risk posed by natural and induced seismicity in the Scientific Assessment region, 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, M6.2 in 1912; Tulbagh-Ceres in the Western Cape, M6.3 in 1969), both well outside the Scientific Assessment area. Thus the occurrence of a felt earthquake within the Scientific Assessment area is considered to be unlikely, and the occurrence of a damaging event to be very unlikely. The area is sparsely populated, apart from the towns of Beaufort West 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. The first western style buildings were erected in this area around 1750 and the fact that some of these buildings have survived till today shows the rarity of damaging earthquakes. Most buildings, including important heritage buildings and dwellings, were built using mud bricks or unreinforced masonry and are thus vulnerable to damage similar to that experienced in Tulbagh in 1969 and in Khuma Township near Orkney in 2014. Thus the consequences of a M>5 earthquake occurring within 20 km of a town is considered to 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 Scientific Assessment area is considered to be low.

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 damaging event to be very unlikely. Thus, the risk posed by earthquakes
in the Scientific Assessment area during the exploration and appraisal phase is considered to be low and not significantly different to the baseline.

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Scenarios 2 & 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 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 microseismic events (M<3) imperceptible to humans, while none of the few felt events have caused any 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 hydraulic fracturing is considered very unlikely to induce a damaging event. Providing hydraulic fracturing is not carried out within a distance of 20 kilometers of a town, the consequences are considered to be slight.

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 hydraulic fracturing. 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. It is thus important that seismicity is monitored for several years prior to any hydraulic fracturing, and that a seismic hazard assessment is performed to provide a quantitative estimate of the expected ground motion caused by natural seismicity. 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 seismic monitoring network be densified in the Scientific Assessment region, 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. Other mitigation measures to be considered should include: disaster insurance, retrofitting of vulnerable buildings (especially heritage buildings, schools and hospitals), enforcement of building regulations, training and equipping of emergency first responders, and earthquake drills in schools and offices.
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 kilometers. 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. It is believed that the Karoo basin contains strata that may contain significant resources of shale gas.

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 microseismic events (M<3) that are barely perceptible on the surface associated with the deliberate formation of fractures to liberate gas (i.e. fracking), to larger events that may alarm residents and cause damage to vulnerable structures such as heritage buildings or buildings built from adobe (mud brick) or unreinforced masonry, typical of the Karoo. It must be emphasised that the larger events (M>3) are almost always associated with the injection of massive volumes of waste water, not fracking.

**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.

Natural earthquakes generally 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 are much shallower than natural events. Earthquakes are generally divided into the following categories: micro M<3, small 3<M<5, moderate 5<M<7, and major M>7.

**Intensity (I)** describes the shaking experienced on the surface. 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 only known study of the impact of hydraulic fracturing on South African seismicity was conducted under the auspices of the Water Research Commission (Kijko and Smit, undated). Kijko and Smit conclude that hydraulic fracturing “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 Scientific Assessment area in the central Karoo region, and advise how best any risk can be mitigated. In particular, the assumptions and conclusions of the Water Research Commission report on the effect on seismic hazard (Kijko and Smit, undated) will be assessed. Mitigation measures to be considered include disaster insurance, retrofitting 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 chapters dealing with Water Resources, Waste Planning and Management, Cultural Heritage, Planning and Infrastructure, SKA and Human Health.

4.1.1 Overview of international experience

There is a large volume of published literature on the subject of shale gas development (SGD) and seismicity. In some instances (e.g. in Oklahoma), earthquake activity increased dramatically in areas where unconventional gas development was implemented. Earthquakes with magnitudes as large as five 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 hydraulic fracturing. It should also be noted that there are cases where damaging earthquakes (e.g. near Gröningen in the Netherlands) are associated with the large scale extraction of oil and gas, but without any fluid injection being practiced.

The Governing Board of the National Research Council (USA) 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 which are relevant to SGD in the Karoo are:

1. Seismic events caused by or likely related to energy development have been measured and felt in twelve American states. However, only a very small fraction of injection and extraction activities at hundreds of thousands of energy development sites in the United States have induced seismicity at levels that are noticeable to the public.

2. The process of hydraulic fracturing as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events. Observations and monitoring of hydraulic fracturing treatments indicate that generally only microseismic 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 wastewater into the subsurface 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 USA. The micro-earthquakes are likely due to slippage along faults, natural fractures, and bedding planes, with the largest probably being fault interactions. The magnitude of most microseisms are in the range M-1.0 to M-1.5 (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, minimize risk, and enhance appropriate readiness when seismic events occur”. The ISWG published a 141 page report in 2015 (Ground Water 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 hydraulic fracturing 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 (one 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 fracturing 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 hydraulic fracturing, and no reports of damage. In the UK Bowland shale incident (De Pater 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 (Liu 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 injected 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 (Mw 0.4–3.9) 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 wastewater (brine) in Ohio produced by hydraulic fracturing 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) hydraulic fracturing of shale formations or coal seams to extract gas and oil, (2) disposal of wastewater from these 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, wastewater disposal is observed to be associated with the largest earthquakes, with magnitudes sometimes exceeding 5. McGarr reports that while permeability-enhancing treatments (i.e. fracking) do induce microearthquakes (i.e. M<3), they are seldom large enough to be felt at the surface. He does, however, note that exceptions were reported by Holland (2013: 1784), De Pater and Baisch (2011), and British Columbia Oil and Gas Commission (2012).

**Figure 4.2: Maximum seismic moment and magnitude as functions of 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 uplift and erosion.

The western Cape Fold Belt is seismically active. The largest instrumentally recorded earthquake was a M6.3 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. Another cluster of events is found near Koffiefontein in the southern Free State. A $M_L 6.2$ 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). On 12 January 1968 and 11 September 1969 events of magnitude $M_L 5.2$ and $M_L 5.4$ took place near Willowmore and Calitzdorp, respectively.

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 $M_L 5.5$ 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 RDP-type housing to strong ground motion.

![Figure 4.3](image_url)

Figure 4.3: Location of recorded earthquakes in southern Africa. Black triangles - locations of SANSN stations; black rectangle – Scientific Assessment region. (Source: Council for Geoscience, 2014)

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 palaeoseismologists 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.

Palaeoseismic 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 twenty-one
lithological units, six soil horizons, and nineteen 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 Mw7.4. It should be noted that there a fair degree
of uncertainty associated with the magnitude assessment, as is the case with all palaeoseismic
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
by earthquakes induced by hydraulic fracturing include:

89. Assessment of related seismicity

(1) An applicant or holder must, prior to conducting hydraulic fracturing, assess the risk of potential
hydraulic fracturing 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 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 hydraulic fracturing 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.

(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 subregulation (6), investigate whether seismic activity occurs and then modify subsequent hydraulic fracturing operations.

(8) The holder must undertake seismic monitoring at the site for a period of 3 years after hydraulic fracturing 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 hydraulic fracturing, 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 100m or more away from well at a comparable depth.
(c) Microseismic sensors must be designed for temperatures between 175-200 degrees C.
(d) Tiltmeter measurements must be taken with an array of tiltmeters, either located in shallow offset wells (10m) 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 hydraulic fracturing report
(1) A holder must compile and submit, to the designated agency and the department responsible for water affairs, a detailed post hydraulic fracturing 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 or be impractical. For example, the meaning of the phrase “fracture behaviour of targeted formations” (clause 89 (1) (b)) should be clarified; and the stipulation that an array of accelerometers must be installed in a monitoring well (clause 112 (8) (b)) should be reviewed, as it is likely that equally good measurements could be obtained from a far cheaper surface array.
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 subsurface area to be explored and exploited from a single drilling pad. Beginning in the 1990s, engineers in the USA 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 hydraulic fracturing are induced by at least three mechanisms:
(i) Cracking or rupturing of rocks in the vicinity of the wellbore that creates microearthquakes of very small magnitude, M<0;
(ii) Interaction between fracking fractures and nearby faults, where the fracking fluid enters the faults zone. This may cause 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 cause 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 Scientific Assessment 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 microseismic 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 ruptured casings.
As noted in the chapter on Water Resources, 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 South African National Seismograph Network (SANSN), the Council for Geoscience has built a database of earthquake locations, which can form the basic baseline data for the Scientific Assessment 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 microseismic 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 (i) determine the expected maximum magnitude of earthquakes (ii) determine the expected maximum ground motion at fracking site and in the region. Assessment 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 from analysis of data recorded on 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.
• Enforce building codes.

4.2.5 Cumulative impacts

Here we consider an extreme scenario where large scale SGD 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 fifty 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.

A risk assessment is an attempt to quantify the losses that could be caused by a particular hazard. It is calculated as follows:

\[ \text{Risk} = \text{likelihood of the hazard occurring} \times \text{seriousness of consequences} \]

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 ($M_{\text{max}}$), 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 $M_L 6.2$ (Koffiefontein, 1912) and $M_L 6.3$ (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. Paleoseismic studies suggest that a $M_w 7.3$ 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 PGA with a 10% probability of being exceeded in 50 years is less than 0.05 g in the Scientific Assessment area, going up to a value greater than 0.2 g in the Ceres region. The Council for Geoscience is in the process of developing new seismic hazard maps of South Africa (Midzi *et al.*, 2016).

Thus the occurrence of a felt earthquake within the Scientific Assessment 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 of Beaufort West 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 mud bricks or unreinforced masonry and are thus vulnerable to damage similar to that experienced in Tulbagh in 1969 and in Khuma Township near Orkney in 2014. Thus the consequences of a $M>5$ earthquake occurring within 25 km of a town is considered to 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 Scientific Assessment 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 Scientific Assessment 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, 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, there is likely to be an increase in the frequency of felt earthquakes in the vicinity of the production wells. The likelihood of induced and triggered seismicity depends on the location of wells in relation to faults, especially pre-stressed faults and also depends on the rate of fracking.

Many thousands of hydraulic fracture wells have been drilled worldwide. Most only caused microseismic 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 hydraulic fracturing is considered very unlikely to induce a damaging event. Providing hydraulic fracturing is not carried out within a distance of 20 kilometers of a town, the consequences are considered to be slight. If hydraulic fracturing is carried out close to a town (say within 10 km) the consequences may be severe.

4.3.2 Earthquake risk matrix

It is perhaps worth considering a worst case scenario, taking the Ceres-Tulbagh earthquake of 1969 as an example. Should a M6 natural earthquake occur with its epicentre within 10 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 such an 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, hydraulic fracturing is highly unlikely to induce such an earthquake. The implementation of mitigating measures could decrease the consequences somewhat.

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 hydraulic fracturing. 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 hydraulic fracturing 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. 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 reduce complaints.

Table 4.1: Earthquake risk matrix

<table>
<thead>
<tr>
<th>Key Strategic Issue</th>
<th>Earthquakes</th>
<th>Without mitigation</th>
<th>With specified mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-issue</td>
<td>Scenario</td>
<td>Area</td>
<td>Likelihood</td>
</tr>
<tr>
<td>Reference Case</td>
<td>Wells within 20 km of towns</td>
<td>Very unlikely</td>
<td>Slight</td>
</tr>
<tr>
<td>Exploration Only</td>
<td>Small Gas</td>
<td>Not likely</td>
<td>Slight</td>
</tr>
<tr>
<td>Big Gas</td>
<td>Reference Case</td>
<td>Not likely</td>
<td>Moderate</td>
</tr>
<tr>
<td>Wells beyond 20 km of towns</td>
<td>Very unlikely</td>
<td>Slight</td>
<td>Low</td>
</tr>
<tr>
<td>Small Gas</td>
<td>Big Gas</td>
<td>Very unlikely</td>
<td>Slight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unlikely</td>
<td>Slight</td>
</tr>
</tbody>
</table>
4.3.3 Previous assessments of seismic hazard owing to hydraulic fracturing

The only known previous study of the impact of hydraulic fracturing on South African seismicity was conducted under the auspices of the Water Research Commission (Kijko and Smit, undated). The report is entitled “Possible Effect of Hydraulic Fracturing on Seismic Hazard in South Africa”. Kijko and Smit conclude that hydraulic fracturing “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. We seek to explain why this is so.

- Kijko and Smit consider the entire region of South Africa, while our study is focused on the Scientific Assessment region in the Karoo. The baseline hazard in Scientific Assessment area is low compared to other parts of South Africa.
- Kijko and Smit 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 two, five and ten; as well as an assessment that combines the four scenarios, assigning weights of 0.15, 0.50, 0.30 and 0.05 to each scenario, respectively. Kijko and Smit “strongly emphasize 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”.
- It is our opinion that the approach used by Kijko and Smit overstates the increase in hazard. International experience based on hundreds of thousands of hydraulic fracturing stimulations worldwide, indicates:
  - Seismicity induced by hydraulic fracturing is transient (hours to days), limited to the immediate area surrounding the wellbore (hectares to perhaps a square kilometer), 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 kilometers.
  - 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 M4. Thus the frequency-magnitude distribution of seismic events induced by hydraulic fracturing 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.

Other mitigation measures to be considered should include:

- Disaster insurance,
- Retrofitting of vulnerable buildings (especially heritage buildings, schools and hospitals),
- Enforcement of building regulations,
- Training and equipping of emergency first responders, and
- Earthquake drills in schools and offices (drop, cover, hold on!).

We recommend that the South African National Seismograph network, operated by the Council for Geoscience, be densified in the Scientific Assessment region, and that surveys of buildings and other structures (e.g. bridges, dams) be carried out before, during and following any SGD activities.

The Council for Geoscience currently operates only two seismograph stations within the Scientific Assessment 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.

The monitoring of seismicity at the well site is normally to 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. Satisfactory depth estimation of shallow, small earthquake can be achieved if the separation between seismic stations is of the order of 2 km. 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 1.3: Relevant legislation, regulation and practice).

4.5 Topics on which information is inadequate for decision-making

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 Karoo (Scientific Assessment region), 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


