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What is the seismic risk of mine flooding?

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Abstract

Increased levels of seismicity are known to occur when water enters cracks in the Earth's surface. This so-called "fluid-induced seismicity" is a phenomenon that has been observed in many non-mining settings (e.g. filling of dams and fluid injection). In South Africa some gold mines are already flooding and many more will fill with groundwater when they close. Preliminary investigations have shown that flooding of mines has already generated increased levels of seismicity.

This paper aims to create awareness that fluid-induced seismicity will become increasingly important in South Africa when closed mines are allowed to flood. The flooding of mines could lead to potentially disastrous seismicity, which poses a safety risk for neighbouring mines and surface communities. However, the seismicity associated with flooding of deep mines has not been thoroughly researched.

There is an urgent need to research the potential relationships between flooding and the magnitude and frequency of triggered and induced seismicity resulting from mine flooding. A thorough understanding of the interaction between flooding and seismicity needs to be obtained so that the impact of mine flooding on safety can be quantified. In particular, the maximum credible earthquake size resulting from the flooding of deep gold mines in South Africa needs to be determined. The identified risks will, in turn, allow appropriate mitigating strategies to be developed. Such strategies will influence South African mine closure policies.

1. Introduction

When a mine starts up, groundwater often needs to be pumped out of the water-bearing strata to enable mining to take place. After the ore has been extracted and the mine closes, the pumping stops and the groundwater is allowed to fill the mine.

In South Africa many deep-level gold mines are reaching the end of their lives and will be allowed to flood. This flooding can result in very high water pressures, which can affect the stability of the natural and mining-induced fractures, causing them to slip and generate seismic events (Ogasawara *et al.*, 2002; Srinivasan *et al.*, 2000; Goldbach, 2009). This can happen because high pore pressures reduce the clamping forces on the fractures, which can cause even previously non-seismic fractures to slip (Figure 1). Seismic activity may continue for a long time once the mines are allowed to flood after closure due to fluid-induced movement along planes of weakness. Such flooding-induced seismicity can result in significant environmental, social, economic and safety risks.

This paper aims to create awareness that fluid-induced seismicity will become increasingly important in South Africa when closed mines are allowed to flood. Historical examples of fluid-induced seismicity in non-mining settings illustrate the phenomenon. The underlying mechanisms for fault slip in the presence of water are briefly outlined. The uniqueness of flooding South Africa's deep mines is discussed and some preliminary observations of fluid-induced seismicity in a South African gold mine are shown. Finally, the seismic risks associated with mine flooding are highlighted, along with the implications for the South African government.

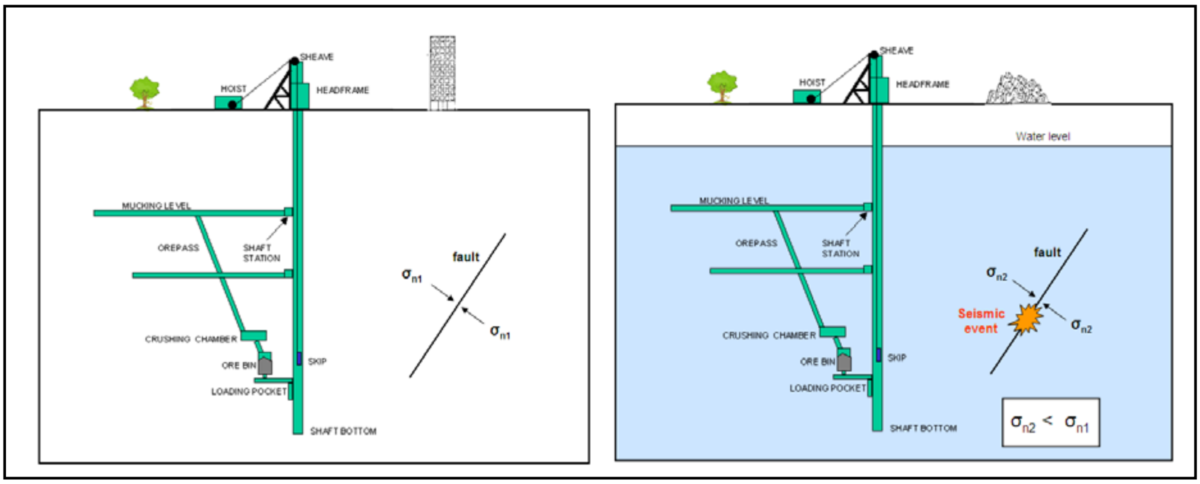

Figure 1. Mine flooding reduces the clamping forces (σ_n) on a fault (right picture) compared to a dry mine (left picture) resulting in mine tremors

2. Fluid-induced seismicity in non-mining settings

Several human activities have resulted in the stimulation of fluid-induced earthquakes, including the filling of reservoirs and the injection of fluids into rocks at depth. Fluid-induced seismicity has been observed to occur in oil-well stimulation (Parotidis *et al.*, 2004; Gibbs *et al.*, 1973; Raleigh *et al.*, 1976), where high-pressure water is pumped into a stimulation well in an oil field in order to increase the oil yield of a nearby production well. Reservoir-induced seismicity is another example where the filling of newly constructed dams has resulted in the onset of seismicity around the dam as water slowly flows into the cracks underneath the reservoir (Gahalaut *et al.*, 2007; Kisslinger, 1976; Assumpçao *et al.*, 2002; Chen and Talwani, 1998; Gupta *et al.*, 1969; Gupta, 1983; Gupta and Iyer, 1984; Gupta *et al.*, 2002). In South Africa, the filling of the Katse Dam resulted in the onset of seismic activity (Brandt, 2000) that necessitated the relocation of nearby rural settlements. Fluid-induced seismicity has also been observed around hydrothermal fields and around geysers (Yamabe and Hamza, 1996; Baisch *et al.*, 2010).

Globally the largest reservoir-induced earthquakes were about magnitude 6, typically occurring after filling of the dam reached its highest water level. Variations in lake level are also often accompanied by fluctuations in seismicity. In all cases, the rocks around the dams were critically stressed before the impoundment and the induced earthquakes appear to be related to pre-existing faults that are re-activated after impoundment. Some case histories of fluid-induced seismicity are briefly described here.

2.1 Fluid injection

2.1.1 Rocky Mountain Arsenal: waste disposal

In March 1962, the U.S. Army started pumping contaminated fluids into a 3.6 km deep rock reservoir at the Rocky Mountain Arsenal, northeast of Denver, Colorado (Healy *et al.*, 1968). Four phases of fluid injection were undertaken between early 1962 and early 1966 (Figure 2). Fluids were pumped into the wellbore at average rates of 7.5 – 21 million litres per month at a bottom hole pressure of around 37 MPa. Seismic activity started about a month after fluid injection began. A significant correlation was noted between the volumes of fluid pumped into the Rocky Mountain Arsenal wellbore and the number of earthquakes detected (Figure 2).

There was also a striking correlation between wellbore pressure and earthquake frequency (Figure 3). The seismicity continued for almost two years after fluid injection was stopped in early 1966. There was no evidence of seismic activity before 1962 similar to the earthquakes that occurred after 1962 (Healy *et al.*, 1968).

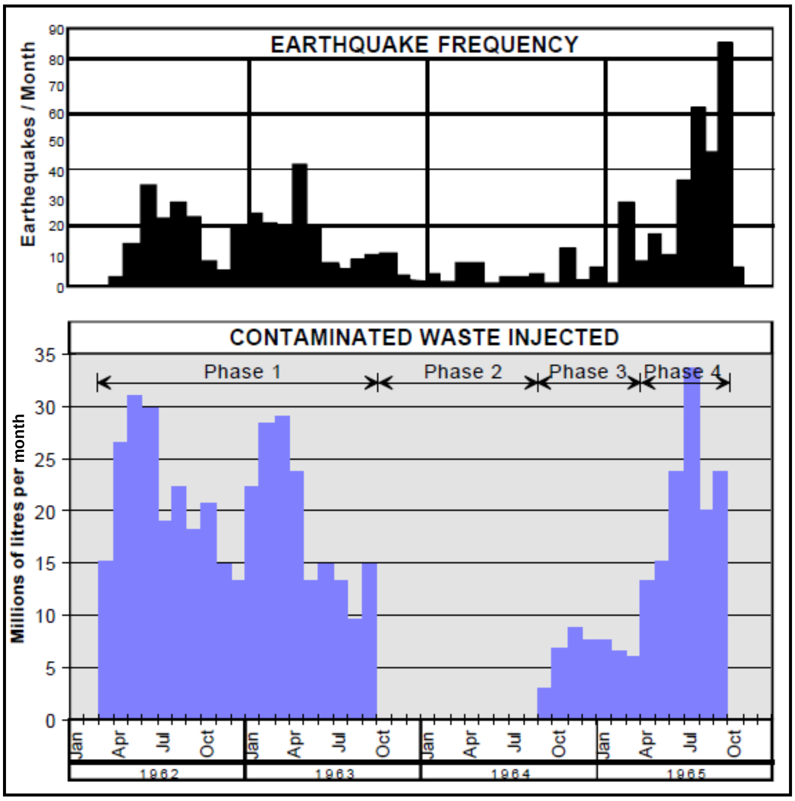

Figure 2. Comparison between Denver earthquake activity and the four phases of fluid injection at the Rocky Mountain Arsenal. Phase 1: 21 Mℓ/month (active pumping). Phase 2: no pumping. Phase 3: 7.5 Mℓ/month (gravity flow only). Phase 4: 17.5 Mℓ/month (active pumping) (after Healy *et al.*, 1968)

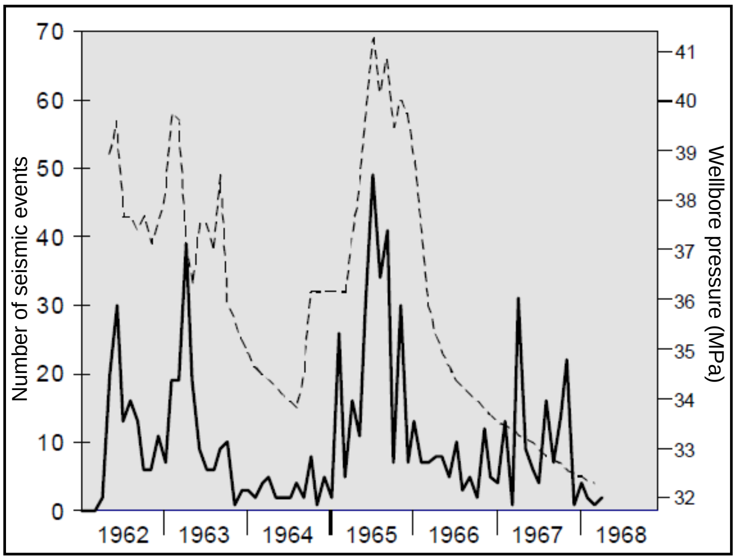

Figure 3. Monthly seismicity (solid line) compared to bottom-hole pressures (dashed line) at the Rocky Mountain Arsenal (after Healy *et al.*, 1968)

Between April 1967 and November 1967, over a year after the Rocky Mountain Arsenal had ceased disposal operations into the deep wellbore, three large earthquakes (magnitude 5.0 to 5.5) shook Denver. Healy *et al.* (1968) concluded that the likely cause of the observed seismic activity was the release of stored tectonic strain energy by the injection of fluids into the basement rocks. Seismic activity stopped shortly after the earthquakes of late 1967 and no further fluid injection was undertaken at the Rocky Mountain Arsenal.

2.1.2 Rangely: oil-well stimulation

Oil was discovered in the Rangely oil field (Colorado) in 1933 and full-scale production from the field began in 1943. Some 481 wells had been drilled into the oil bearing Weber sandstone formation (350 m thick, 1900 m below surface) before extraction from the field was completed in 1949.

Water-flooding of the Rangely field began in 1957 to artificially stimulate secondary oil production in order to acquire oil reserves that could not be obtained by conventional means. Water was injected under pressure into converted oil wells (so-called stimulation or injection wells) to force oil in the reservoir towards low pressure wells from where it could be pumped to surface (production wells). By September 1969 water was being injected into a total of 202 wells. Seismic activity in the Rangely area appeared to increase during secondary oil production by fluid injection (Scholz, 1990, p. 324; Gibbs *et al.*, 1973; Raleigh *et al.*, 1976). A large number of seismic events was identified as originating from the Rangely oil field (Figure 4). Much of the seismicity coincided with the southern extent of a fault that cuts through the centre of the field.

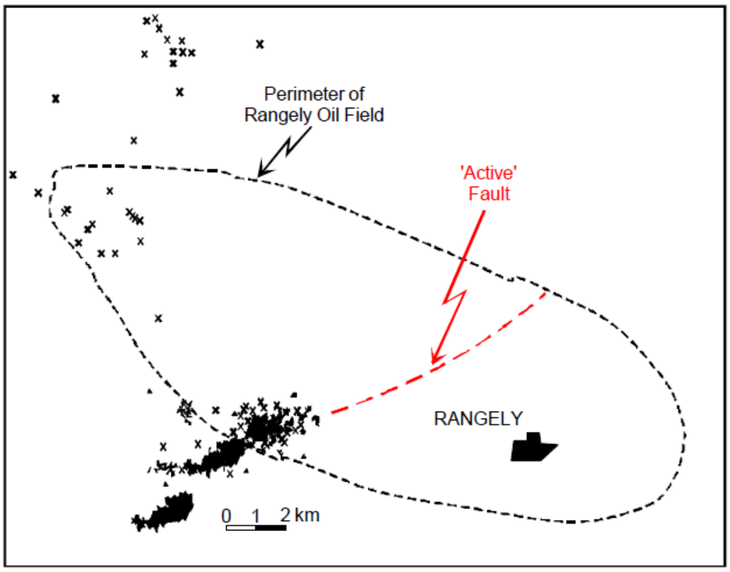

Figure 4. Earthquakes located at Rangely (October 1969 – November 1970)

However, it was not so much the absolute value of the fluid injection pressure that affected the seismic activity as the changes in the amount of fluid injected that caused changes in the induced seismicity. An increase in the fluid injection rate caused the amount of seismic activity to also increase. The largest event recorded was a magnitude 3.1.

2.1.3 Matsushiro: fluid injection

In 1970 a fluid injection scientific experiment was undertaken at Matsushiro, Japan. Almost 3 million litres of water was pumped into an 1800 m deep wellbore over a period of one month. The borehole intersected the Matsushiro fault zone. Injection pressures were less than 5 MPa and flow rates varied from 120 ℓ/min to 300 ℓ/min. A significant amount of induced seismicity was recorded with a maximum event magnitude of 2.8 reported (Ohtake, 1974).

2.1.4 Texas: hydraulic fracturing

House and Flores (2002) reported on a fluid injection experiment into a sedimentary rock formation in eastern Texas, which aimed to demonstrate the use of hydraulic fracturing to dispose of waste fluids. An injection well and two seismic monitoring wells were drilled to a depth of 1460 m.

Three injection cycles lasting 20-30 hours each were performed over a period of 130 hours. Approximately 2400 m^3 bentonite slurry was injected at rates of 1500-2000 ℓ/min in each cycle at pressures between 20.7 MPa and 24.1 MPa (Figure 5). House and Flores (2002) recorded 2894 event triggers during the fluid injection experiment. During each injection cycle the recorded seismicity increased. The magnitudes were estimated to be between -2 and 2.

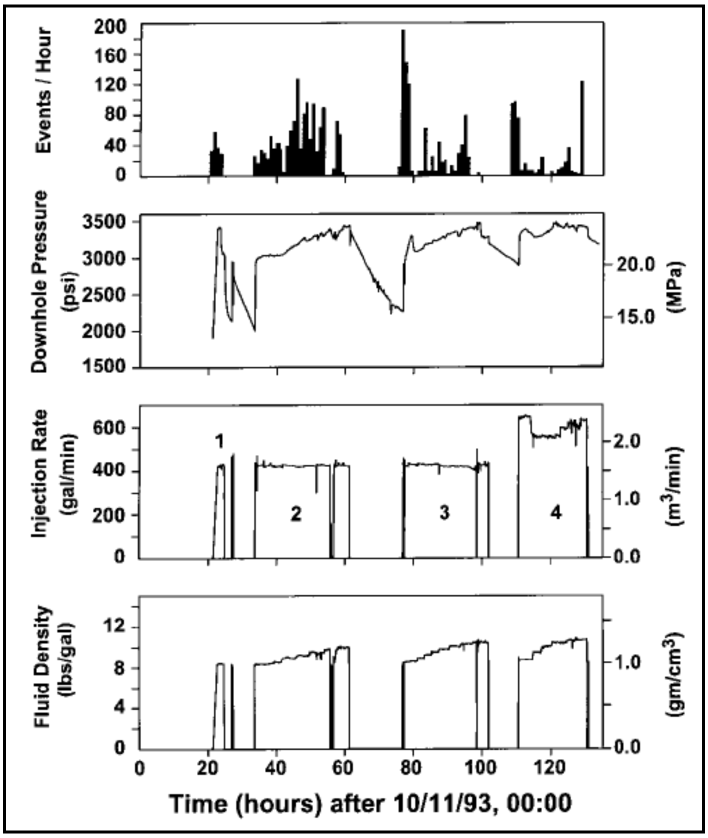

Figure 5. Time histories of fluid injection experiment in east Texas (after House and Flores, 2002). Top to bottom: seismic event rate, injection pressure, injection rate, fluid density

2.2 Filling of reservoirs

Numerous examples of earthquake activity associated with the filling (impoundment) of man-made dams exist. One of the most devastating was the magnitude 6.3 earthquake that occurred at Koyna dam, India, on 10 December 1967 (Gupta *et al.*, 1969). While the dam did not fail, the earthquake resulted in over 200 fatalities, 1500 injuries and thousands were made homeless. Three examples of seismicity associated with reservoir filling are briefly discussed here.

2.2.1 Nova Ponte reservoir

In a study of 16 Brazilian reservoirs, Assumpção *et al.* (2002) reported that the largest recorded reservoir-induced earthquake was magnitude 4.2. Figure 6 shows an example of reservoir-induced seismicity associated with the filling of the Nova Ponte reservoir. An “initial” period of seismic activity was observed 1 – 2 years after filling began, as well as “delayed” activity 3 – 5 years after impoundment. Magnitude 3.5 and 4.0 earthquakes were induced during the impoundment.

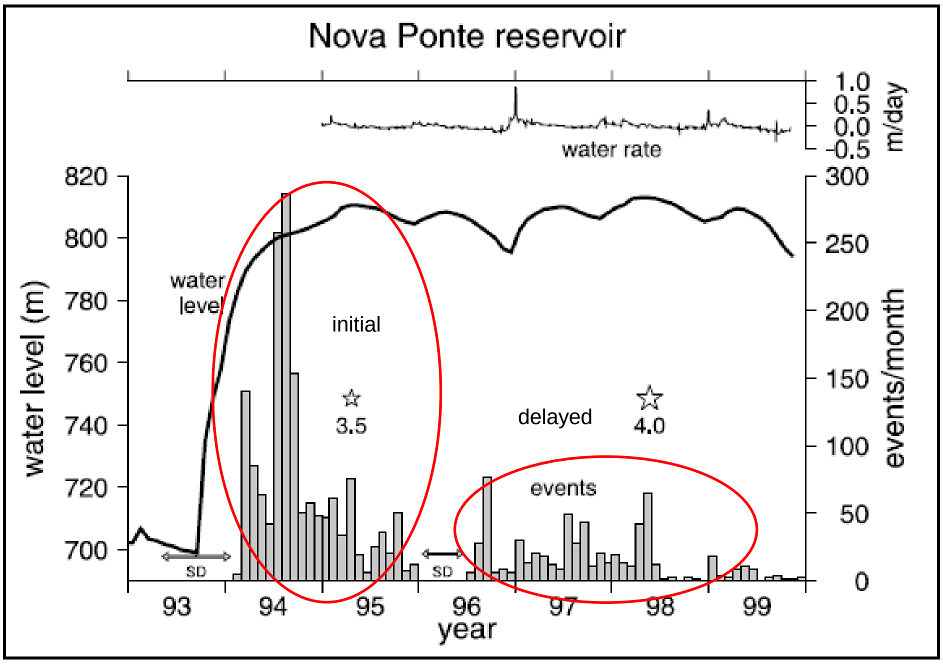

Figure 6. Seismicity vs. water level at the Nova Ponte reservoir in Brazil (after Assumpção *et al.*, 2002)

2.2.2 Rihand dam

Gahalaut *et al.* (2007) analysed the correlation between the times of high water levels and the occurrence of earthquake frequency for the 92 m high Rihand dam, which was built in 1962 and is the second largest reservoir in India.

The temporal variation of earthquakes that occurred within 30 km of the reservoir is shown in Figure 7, along with the seasonal fluctuations in the reservoir water levels. There was a time lag of a few months between earthquake frequency and water level, suggesting that the earthquake occurrence seemed to clearly be influenced by annual (10 – 12 m high) changes in the reservoir level.

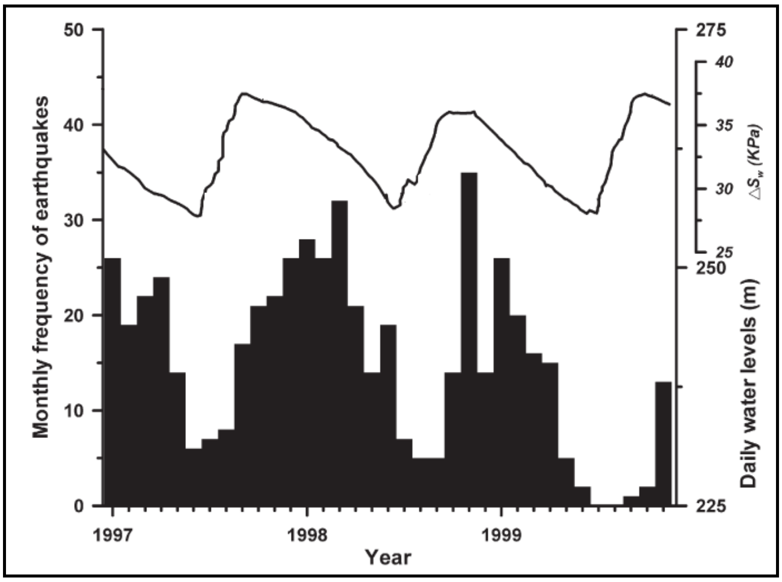

Figure 7. Earthquake frequency vs. water level fluctuations at the Rihand dam, India (after Gahalaut *et al.*, 2007)

Gupta *et al.* (1969) also reported a correlation between the reservoir levels and the seismicity at the Koyna dam. Enhanced seismic activity was observed after a certain time lag of a few months, which correlated with the height of the water level in the reservoir and the duration for which it was retained. However, Gupta *et al*. (1969) found that not just the fluctuations in the water level, but also the weekly *rate* of fluctuations influenced the chance of induced seismicity. A higher filling rate generated more seismicity.

2.2.3 Açu reservoir

El Hariri *et al.* (2010) studied a well-recorded example of reservoir-induced seismicity from the Açu reservoir in Brazil, which was impounded in 1983. The water level varies by 3 – 6 m during the annual rainy season. It rises rapidly over ~75 days, peaks for 1-2 days and gradually decreases until the next rainy season. An increase in seismicity 3 – 4 months after the water level peaked was reported (Figure 8).

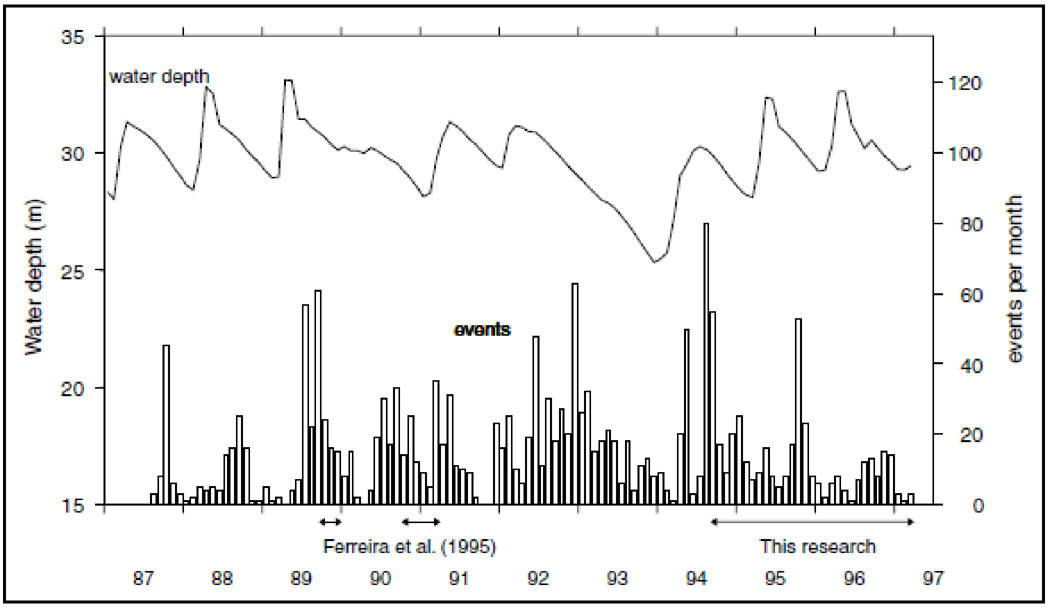

Figure 8. Monthly water level fluctuations and seismicity at Açu reservoir, Brazil (after El Hariri *et al.*, 2010)

The absolute water depth, time since the previous water level peak and rate of water level rise (supporting the observations of Gupta *et al.*, 1969) all affected the triggering of seismicity. The depth of the seismicity was 1.5 – 2.8 km and the time delay between the water level peak and the initiation of seismicity increased with the increasing depth of the seismicity.

2.3 In-mine fluid injection

In the late 1980s and early 1990s the Chamber of Mines Research Organisation conducted a number of field experiments into controlled fault slip in mines using water injection (Lightfoot and Goldbach, 1995).

The aim was to induce regular amounts of small shear slip on existing fault surfaces in mines that had the potential to produce large (M>3) seismic events. By inducing numerous smaller events (magnitude 0 to 1) through water injection, the stored strain energy due to mining was to be dissipated in a controlled manner, thus minimising the potential damage associated with rockbursts resulting from slip on the fault.

An intricate mobile pump system was developed that could deliver water at rates of 120 ℓ/min and pressures of up to 30 MPa through four wellbores, which intersected the fault surfaces. These pressures and flow rates were similar to historical examples of wellbore injection which generated large seismic events.

Figure 9 shows a plan view of one of the experimental field sites where fluid injection was performed on two target faults. Unfortunately, during the seven years of field trials using water to induce controlled fault slip, no events of a magnitude greater than zero were recorded. However, numerous micro-seismic events (M<0) that could confidently be claimed to have been generated by fluid injection were induced (Figure 10).

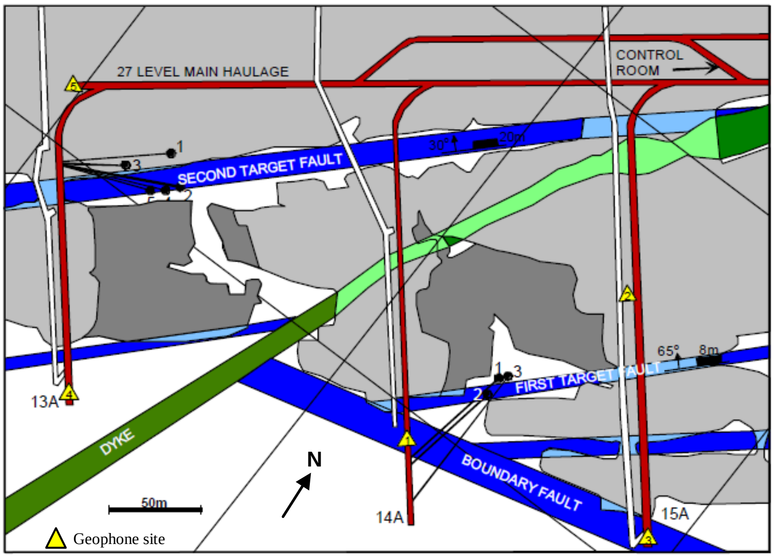

Figure 9. Plan of a fluid injection field site showing wellbores drilled onto two target faults (from Lightfoot and Goldbach, 1995)

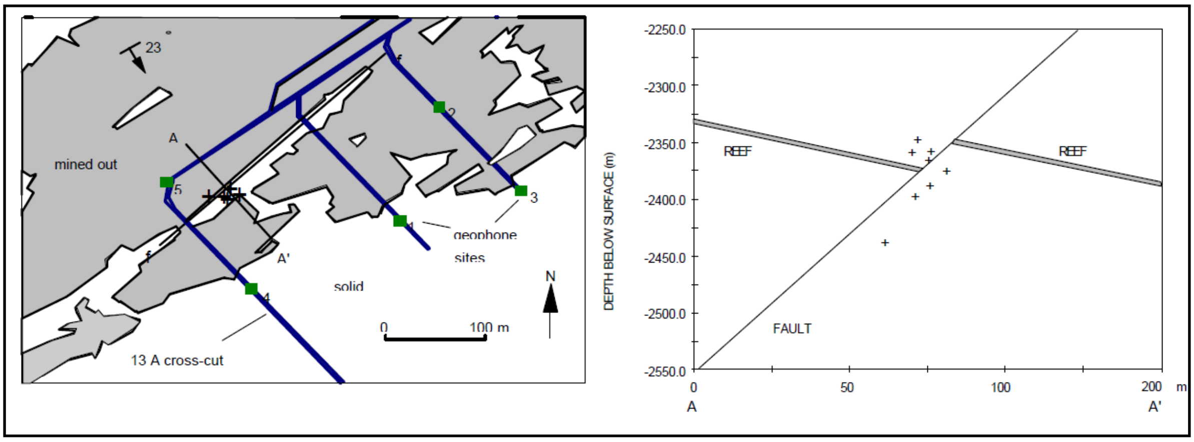

Figure 10. Locations of induced micro-seismic events (+ symbols) due to fluid injection in plan (left) and in section (right) (from Lightfoot and Goldbach, 1995)

The in-mine experiments with fluid-induced seismicity showed that fluids could indeed be used to induce seismic events. However, the reason that only micro-seismic events were generated was ascribed to the unsaturated nature of the in-mine joint systems. Fluid flow in unsaturated natural joint systems is through distinct channels and there is little interconnectivity between relatively closely spaced wellbores in systems dominated by channel flow.

However, large seismic events would indeed be possible in fully saturated joint systems where the pressurisation radii of water on fault surfaces were much larger. Such conditions would exist when large-scale flooding of deep, worked-out mines, was to take place.

3. Triggering mechanisms of fluid-induced seismicity

Earthquakes result from slip on geological faults. Geological faults slip when the shear stress acting parallel to the fault surface exceeds the natural resistance to shear of the fault. This is expressed in Equation 1. A fault will thus slip, if

$$\sigma_s \geq \tau_s \tag{1}$$

where σ_s is the shear stress acting on the fault surface and τ_s is the shear strength of the fault surface.

The resistance to slip along a fault is a function of the cohesive strength acting across the surface and the friction angle of the discontinuity. The strength of such a fault under deviatoric loading is generally assumed to be given by the Mohr Coulomb relationship in Equation 2.

$$\tau_s = c_0 + \sigma_n \tan\phi \tag{2}$$

where σ_n is the normal stress acting on the fault surface, ϕ is the friction angle of the fault surface and c_0 is the cohesive strength acting between the two sides of the fault surface.

The state of stress in a rock mass can be represented graphically in terms of the major (σ_1) and the minor (σ_3) principal stresses together with the Coulomb failure envelope for a fault (assuming zero cohesion) on a Mohr-Coulomb diagram (Figure 11).

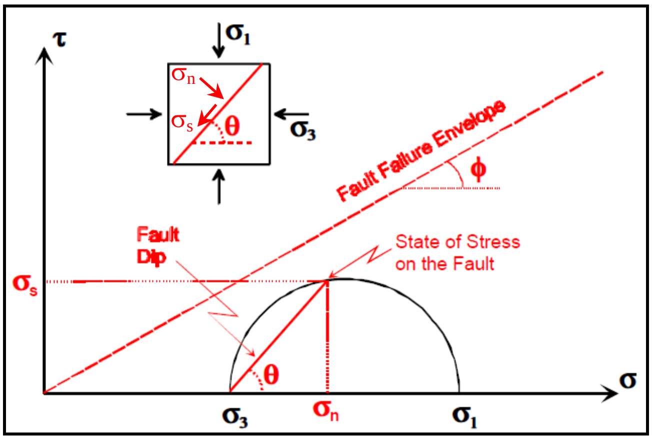

Figure 11. State of stress in a rock mass represented on a Mohr-Coulomb diagram

In order for induced seismicity to occur, a fault must be subjected to substantial shear stress, which is just below the shear strength of the fault (i.e. critically stressed). Slip can be induced by either increasing the shear stress or by reducing the strength of the fault surface. The strength is dependent on the effective normal stress that confines the fault. An increase in pore pressure can decrease the effective normal stress, allowing the pre-existing near-critical shear stress to drive the fault displacement and initiate slip.

If water pressure is applied to the fault aperture, it will counteract the strengthening effect of the applied normal stress acting on the fault surface. The resultant normal stress acting on the fault is known as the effective stress and the fault shear strength is correspondingly reduced (Equation 3)

$$\tau_s = c_0 + (\sigma_n - \sigma_{pp}) \tan\phi \tag{3}$$

where σ_{pp} is the water pressure.

Fluid pressure has the effect of weakening a fault by reducing the normal stress, thus increasing the potential for slip under deviatoric loading (Figure 12). For isotropic rocks, the size of the Mohr circle representing the stress state in the rock mass does not change; it simply shifts to the left by an amount equal to σ_{pp}. The water pressure has no effect on the shear stress acting on the fault surface. As the pore pressure increases, the Mohr circle moves to the left by an amount equal to the pore pressure, and failure will occur when the circle intersects the failure envelope.

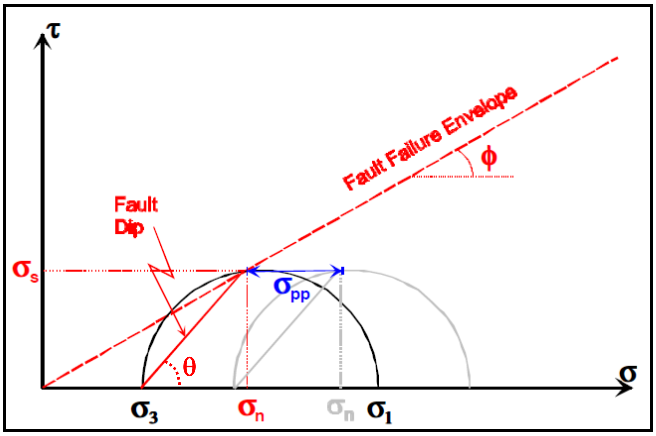

Figure 12. State of stress on a fault surface after the introduction of a pore pressure σ_{pp}

Most of the research agrees that the two main contributing triggers of reservoir-induced seismicity are an initial *increase of shear stresses* (due to the added weight of the water in the reservoir) and a delayed effect of *pore pressure diffusion* (where the increased pore pressure causes Mohr-Coulomb failure through decreased effective stress). The initial and delayed seismic activity commonly observed after dam impoundment (as seen in Figure 6) are often ascribed to these two mechanisms. However, in both cases the seismicity can only occur if the rock is critically stressed close to its peak strength.

Several conditions must be met in order for fluids to initiate earthquakes. The most important condition is the presence and orientation of a regional tectonic or local (e.g. mining-induced) stress state, which is close to the breaking strength of the rocks. Secondly, the rock must be porous enough to be able to accept fluids, but the permeability must be low enough to allow pore pressure build-up (the quartzites in South Africa's gold mines meet this requirement, where the porosity results from the fracture system in the crystalline rocks, which are otherwise impermeable).The penetration of fluids into the rocks must be at such rates and pressures that the formation pore pressures are significantly increased over a large area.

Shapiro *et al.* (2003) found that pore pressure increases as low as 1 kPa – 100 kPa were able to trigger seismicity. Kisslinger (1976) reported that earthquakes can be triggered by increased pore pressures as low as 200 kPa – 300 kPa, while the largest magnitude 6 earthquakes were induced when the pore pressures were 1.0 MPa to 1.5 MPa.

Of course, there will be other factors at play. In addition to the hydrostatic pressure changes, there will be chemical changes, such as oxidation, hydration, stress corrosion and dissolution (Chen and Talwani, 1998; Kisslinger, 1976) – all these processes can weaken a fault. The permeability of the fault aperture and the diffusion of the water into the rock mass will also impact on fault stability.

It must also be realised that fluids travel along tortuous pathways in a fractured rock mass with varying hydraulic diffusivity and permeability, so that the resultant pattern between fluid migration and induced seismicity can become quite complex.

4. What makes the flooding of South African mines unique?

While fluid-induced seismicity has been observed and studied globally in a number of non-mining settings, seismicity associated with mine flooding is different.

Although the learning from oil-well stimulation and dam impoundment will indeed be relevant, seismicity associated with flooding of mines is unique in many respects:

- Firstly, South Africa has some of the deepest mines in the world and not much is known about the level and size of potential fluid-induced seismicity that is expected to occur once these deep, old mines are allowed to flood.
- The volumes of water and the pressures involved are much greater than is the case for oil-well stimulation, for instance.
- South African mines are not only deep, but extensive regions of high stress exist in the mined out areas, regions which could easily slip when exposed to high water pressures.
- Support pillars that were stable during dry mining conditions could become unstable when wet.
- Another unique factor is the proximity of old mines to the Johannesburg metropole. This point is particularly relevant in the light of gold mining restarting beneath Johannesburg.

While there have been some superficial case studies of mine flooding, e.g. in the Kolar gold field in India (Srinivasan *et al.*, 2000), no detailed study of seismicity associated with flooding of deep mines has ever been conducted anywhere.

5. Evidence of fluid-induced seismicity in a South African mine

Fluid-induced seismicity has already started to occur in South Africa 's gold mines. Goldbach (2009) reported how monitoring of mining-induced seismicity in a dry production area of a deep-level South African gold mine revealed additional seismic activity in an adjacent worked-out part of the mine that was being allowed to flood. A plan view of the mine is shown in Figure 13.

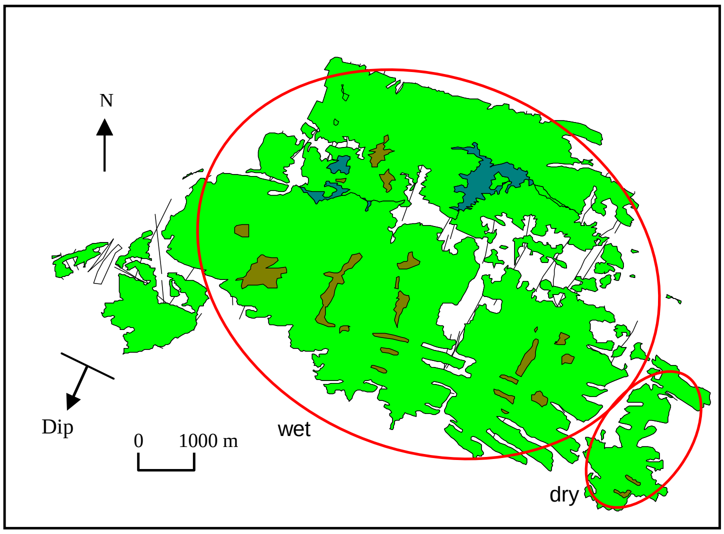

Figure 13. Mine plan showing “dry” production area and “wet” flooding area

Figures 14 and 15 show the seismicity that was recorded over a five-year period (August 1999 to October 2004) in the “dry” production area and the “wet” flooding area, respectively.

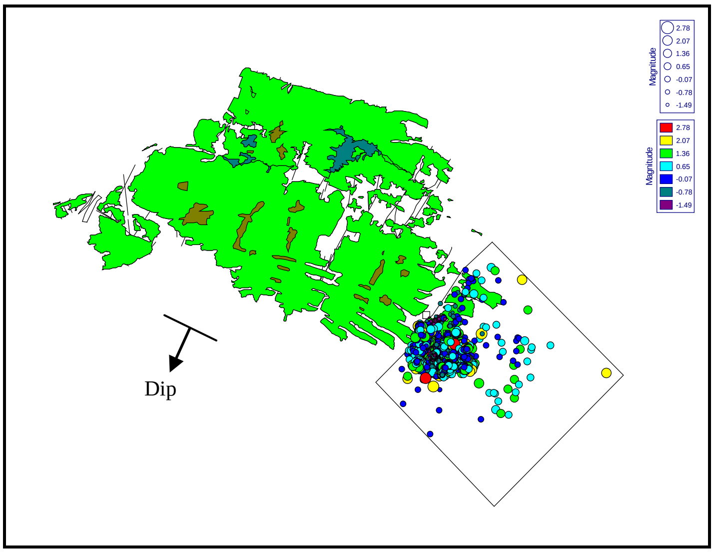

Figure 14. Seismicity recorded in the "dry" production area

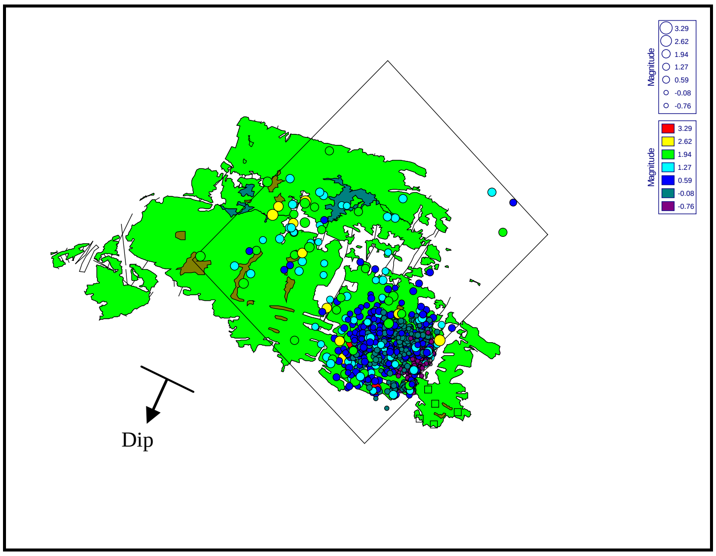

Figure 15. Seismicity recorded in the "wet" flooding area

Almost all the seismic events in the wet area located on-reef. A striking discovery was that much of this seismicity migrated up-dip over a period of approximately 18 months, between September 2000 and February 2002. Figure 16 attempts to illustrate this migration in 100-day snapshots.

A time history graph of the seismic events shows a substantial increase in the event rate over this 18-month period, followed by a rapid decrease thereafter (Figure 17). By contrast, the time history graph for seismic events occurring in the dry mining area shows an almost constant event rate over this period.

In addition to the characteristic differences in the time histories between the two areas, further distinctions were observed. For instance, the daily event distribution of the seismic events which located in the flooding area shows a fairly random number of events having occurred on any particular day of the week (Figure 18). The diurnal distribution of these events shows that they also occurred randomly throughout the day.

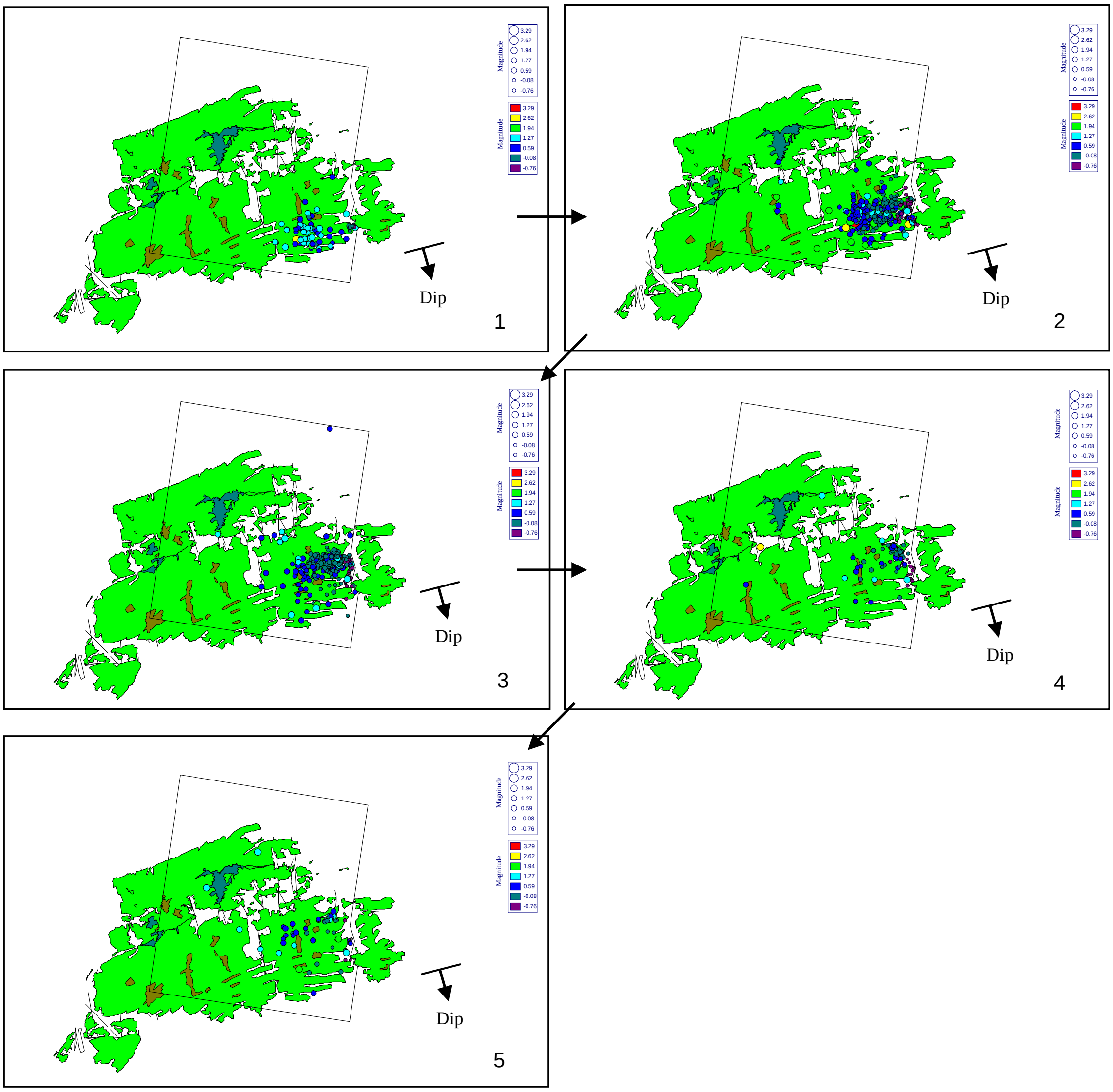

Figure 16. Seismicity recorded in the "wet" flooding area over an 18-month period in 100-day snapshots

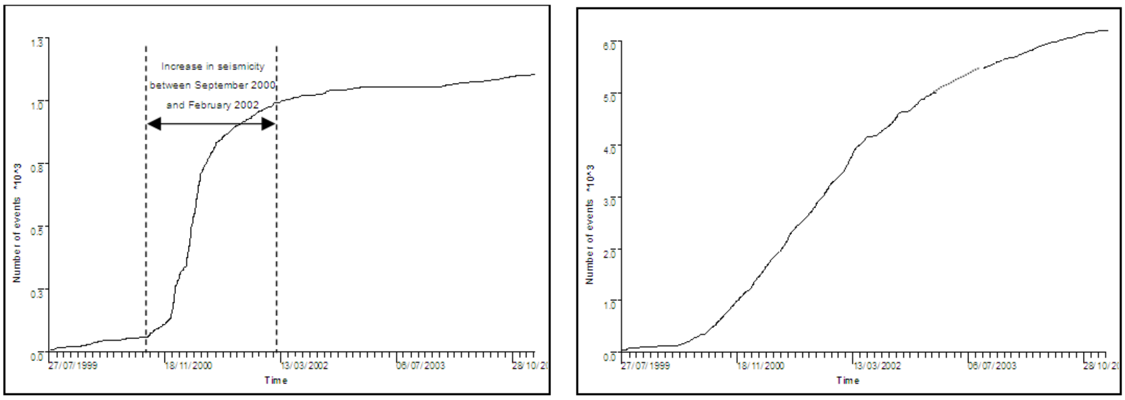

Figure 17. Time history of seismicity recorded in the wet flooding area (left) vs. the dry mining area (right)

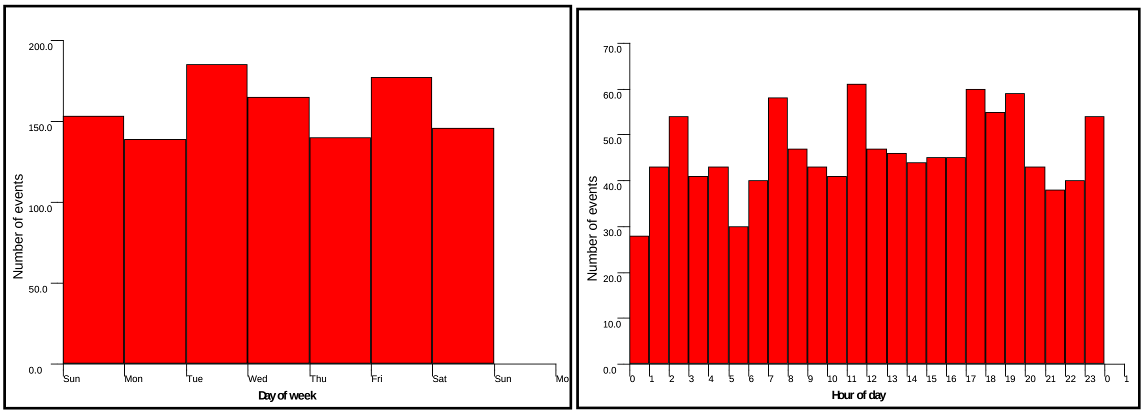

Figure 18. Daily (left) and diurnal (right) event distributions of the seismic events which located in the wet flooding area

By contrast, the corresponding distributions for seismic events occurring in the dry mining area exhibit a very distinct pattern that can be related to the mining processes. Figure 19 shows relatively few seismic events occurred on Saturdays and Sundays – days on which little or no mining took place. A gradually increasing number of seismic events took place between Mondays and Fridays as the production activity increased after a weekend. The diurnal event distribution in Figure 19 also displays a noticeable peak in seismicity during blasting time (18h00 – 19h00), followed by an exponential decay in the event rate. Both these distributions are typical patterns of seismicity occurring as a result of the rock mass response to active mining operations.

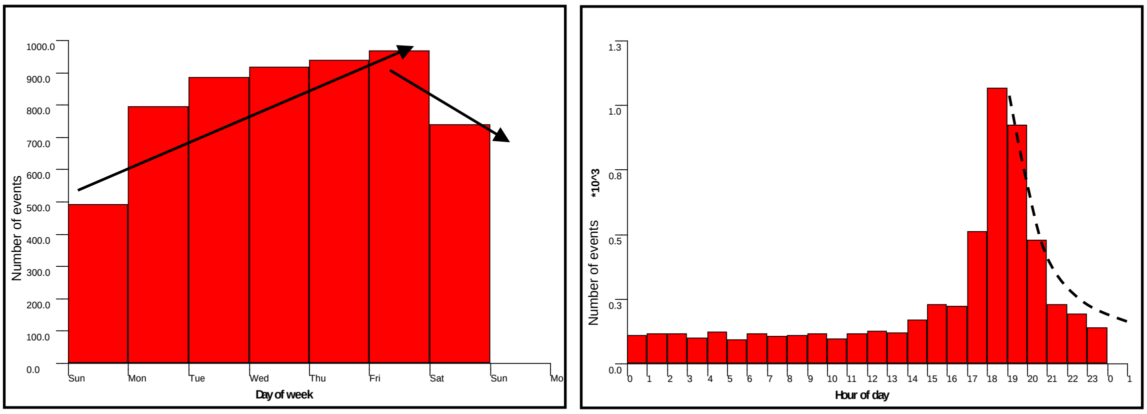

Figure 19. Daily (left) and diurnal (right) event distributions of the seismic events which located in the dry mining area

It was evident that the seismicity in the wet area exhibited distinctly different patterns to that in the dry mining area. But how well did the observed seismic patterns correlate with the flooding?

Figure 20 shows the elevation of the water level together with the depth of the seismic event locations in the flooding area as a function of time. A dense cluster of seismic events is observed in Figure 20 between September 2000 and February 2002. These seismic events started approximately 14 months after flooding commenced and their locations migrated upwards – initially rapidly, but later at a slower rate, eventually coinciding with the elevation of the water level by February 2002. Thereafter the number of seismic events decreased, but their vertical locations remained largely below the elevation of the water level, indicating that seismicity continued in the deeper levels, albeit at a much reduced rate.

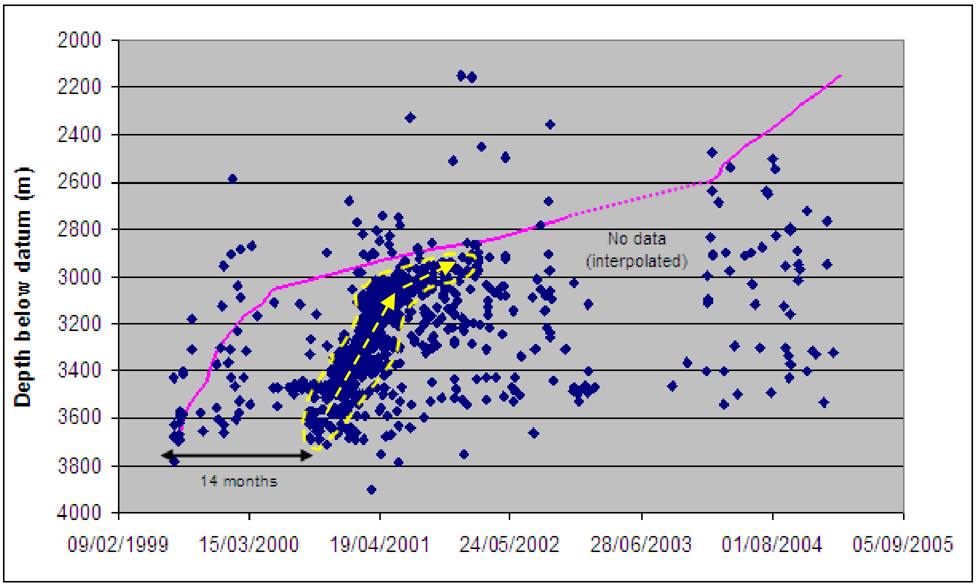

Figure 20. Elevation of water level (solid line) and depth of seismic event locations (diamond symbols) in the flooding area. Note the upwards migration of a cluster of seismic events (dashed line) between September 2000 and February 2002

This correlation between rising water level and seismicity provided convincing evidence that the events were happening as a result of the rising water levels and that they must therefore be fluid-induced.

As described in section 2 of this paper, a delay in the onset of the seismicity is commonly observed after filling of reservoirs and following wellbore fluid injection. As water flows into existing fractures into the rock mass below a dam, a finite amount of time is required (depending on the permeability of the rock) for the rock mass to become saturated and before the pore pressures are sufficiently high to initiate slip (pore pressure diffusion). Similarly, the rapid increase in seismicity in the flooding area of the mine did not commence immediately with the onset of flooding. Shortly after the flooding began a few seismic events were induced. However, there was a 14-month delay before the onset of major seismic activity in September 2000 (Figure 20). These events initially located in the deepest part of the mine, rapidly migrated upwards and eventually “caught up” with the prevailing water level by February 2002. The seismic “front” therefore lagged behind the rising water level in space and in time. It would appear that the volume of water and the associated water pressure needed to reach certain critical values over a period of 14 months before the pore pressures were sufficiently high to induce seismic events.

The maximum credible earthquake magnitude that is likely to be associated with flooding of deep mines is unknown at this stage. In the case study presented here, the largest seismic event that was recorded in the flooding area was magnitude 3.3 (which occurred during the period of intense seismic activity between September 2000 and February 2002), while the largest event in the adjacent mining area was magnitude 2.8. The head of water was not more than 600 m at the time of the large events, suggesting that slip occurred under water pressures of less than 6 MPa. Similar induced seismicity occurred at the Matsushiro experiment where a magnitude 2.8 seismic event occurred at wellbore pressures of 5 MPa.

6. Risks and consequences of fluid-induced seismicity in gold mines

On 9 March 2005 the largest ever South African mining-related earthquake (magnitude 5.3) hit the town of Stilfontein. The seismic event killed two miners at Hartebeestfontein mine and caused structural damage to two commercial properties, three blocks of flats, the civic centre and 25 houses (Figure 21). The damage to buildings was estimated at R 20 million – R 30 million. The insurance damage was estimated at R 500 million. Around 3200 miners were evacuated under difficult circumstances. DRDGold liquidated its Stilfontein mines after the earthquake. About 6500 workers were left without jobs, affecting the livelihood of some 100 000 South Africans who depended on the income of these miners. Approximately 2300 families were left destitute after the closure of the mine. Some 230 000 ounces of gold a year were sterilized, translating into a lost revenue of R 1.8 billion per annum for the South African economy.

Figure 21. Damage to buildings in Stilfontein following a magnitude 5.3 mining-related earthquake (from Durrheim *et al.*, 2007)

The Stilfontein event was not related to any flooding, but it did show that mining activity is able to generate moderately-sized earthquakes. In the context of flooding-induced seismicity an important unanswered question is: *"Can earthquakes the size of the Stilfontein event, or larger, be triggered by water?"*

So severe was the Stilfontein event that the Chief Inspector of Mines at the time commissioned an investigation into the risks to miners, mines and the public, posed by large seismic events in South Africa's gold mining areas. Durrheim *et al.* (2006) reported on the findings of the commission. In October 2007 the President of South Africa ordered an industry audit of mine safety in order to determine the risks associated with mining. The South African Government is clearly serious about addressing mine safety. Against this political background, it is important to understand the potential impact of seismicity as a result of flooding of old mines, as it impacts on national mine safety targets and mine closure plans.

A particular concern in the investigation was the relationship between mine water and seismicity, because fluid-induced seismicity may occur as mines approach the end of their lives, cease operations and allow the underground workings to be flooded with groundwater. As we have seen, if a fault is permeable to fluids, flooding can increase the pore fluid pressure in the fault aperture, diminishing the effective stress clamping the fault, and decreasing its stability. Consequently, seismic events are likely to be triggered as the water level rises in mines that have been closed and allowed to flood. Seismicity is expected to decrease once the water table stabilizes, but may continue for many years.

The pumping of water out of mines is expensive. It costs each mine R 6 million – R 8 million per month to pump 30 million – 75 million litres of water out of the mine every day (*Business Report*, 2005; *The Star*, 2005; Sheqafrica.com, 2009; *Miningmx*, 2009). Who will continue to carry these costs once the mines are worked out? There is thus a strong motivation for mines to be allowed to flood once the ore reserve has been exhausted. Once mines close, the State may have to bear the expected (indefinite) monthly pumping cost of R 6 million – R 8 million for each mine to prevent flooding-induced seismicity.

Alternatively, the consequences of allowing a mine to flood could be an earthquake that is large enough to cause damage to a big city or metropole, such as Johannesburg. Already seismicity near the old mining areas south of Johannesburg is much higher than areas more than 10 km from mining areas (Spottiswoode *et al.*, 2009) – this increase in seismicity may be associated with gradual flooding of the Central Rand Basin. The Central Rand Gold mining company has recently restarted gold mining activities beneath Johannesburg. No-one knows whether Johannesburg will experience an earthquake the size of the Stilfontein event once Central Rand Gold has closed and the mine floods. But, if it does, the consequences could be severe. It is therefore in the national interest that the risks associated with fluid-induced seismicity be understood before many South African mines will close.

Durrheim *et al.* (2006) argued that it was unlikely that any event triggered by water will have a greater magnitude than the events that occurred during active mining. The maximum expected magnitude for mining-related events in South Africa has been estimated to be around 5.5 (Shapira *et al.*, 1989). It is therefore considered unlikely that events with magnitudes larger than 5.5 will occur in gold mining districts in South Africa. Nevertheless, Durrheim *et al.* (2006) strongly recommended that further research should be conducted into the relationship between seismicity and flooding.

7. Implications for the South African government

The risks associated with fluid-induced seismicity need to be quantified now. We need funding for research that establishes the potential relationships between flooding and the magnitude and frequency of seismicity resulting from mine flooding.

A thorough understanding of the interaction between flooding and seismicity will allow the impact of mine flooding on safety to be determined. In particular, the maximum credible earthquake size resulting from the flooding of deep gold mines in South Africa needs to be determined. The identified risks will help the South African government to develop mitigating strategies to protect mine workers and the South African public from large fluid-induced seismic events. Such strategies will allow the mine closure policies of the Department of Mineral Resources to be reviewed, particularly regarding water management towards eventual mine closure.

The results from this research will also have ramifications for Eskom as it seeks to find alternative ways of generating electricity. One of Eskom's current projects is to investigate flooding old mines with water, using a "high head underground pumped storage scheme" (HHUPSS) as a means of driving a turbine to generate electricity during peak demand (*Mining Weekly Daily News*, 2008a; *Mining Weekly Daily News*, 2008b). Fluid-induced seismicity resulting from the large volumes and pressures of water needed for such a project will impact on the viability of a HHUPSS.

The findings from this work will also be relevant to carbon capture and storage (CCS, also known as CO_2 sequestration), a process whereby greenhouse gases like carbon dioxide are removed from the atmosphere and stored underground. The physical state of CO_2 varies with temperature and pressure. It is a gas under ambient conditions, but it becomes a liquid at greater depth. At the pressures and temperatures required for sequestration reservoirs, CO_2 becomes a supercritical fluid. One of the unknown risks in CCS is whether the fluid CO_2 is capable of inducing seismicity in the storage reservoir, similar to the observations made with fluid-induced seismicity in dams and oil-well stimulation (Sminchak *et al.*, 2002; Benson and Cole, 2008). This aspect is particularly relevant in the light of the recent establishment of the South African Centre of Carbon Capture and Storage (*Engineering News Daily News*, 2009). One of the initial outputs of the centre is the publication of a "*South African Carbon Dioxide Storage Atlas*", which identifies potential sites for the possible future storage of CO_2 in South Africa (*Engineering News Daily News*, 2008).

8. Discussion and conclusions

The aim of this paper is to highlight that fluid-induced seismicity will become increasingly important in South Africa when closed mines are allowed to flood. Such flooding-induced seismicity can result in significant environmental, social, economic and safety risks.

While fluid-induced seismicity has been observed globally in other settings (e.g. filling of dams, fluid injection and hydrothermal fields), no detailed study of seismicity associated with flooding of deep mines has ever been conducted anywhere. It is possible that mine flooding could lead to potentially disastrous seismicity, which may result in high continuous pumping costs by the State to prevent or -contain flooding.

Preliminary investigations have shown that flooding of mines can generate increased levels of seismicity. A case study showed that the spatio-temporal signature of fluid-induced seismic events is characteristically different from normal mining-induced events. In particular, a delay between the start of flooding and the onset of fluid-induced seismicity was observed. Thereafter, a rapid increase in seismicity was observed, which was accompanied by an up-dip migration of the event locations from the deeper parts of the flooded mine to shallower elevations. The seismic event rate reduced once the seismic front had caught up with the rising water level.

The flooded region generated large magnitude seismic events (M>3), which occurred at 6 MPa water pressure. Similar induced seismicity occurred at the Matsushiro experiment where a magnitude 2.8 seismic event occurred at wellbore pressures of 5 MPa. However, seismic events with magnitudes larger than 5 were induced at the Rocky Mountain Arsenal where injection pressures approached 37 MPa. Such water pressures are likely to occur in the bottom of 4 km deep gold mines when they are allowed to flood after closure.

"Will similar magnitude 5 seismic events be induced or triggered when 4 km deep mines flood?" At this stage we don't know. The damage caused by the magnitude 5.3 mining-related earthquake to the town of Stilfontein suggests that such large events can be destructive.

I therefore propose that detailed research needs to be conducted, which establishes the potential relationships between flooding and the magnitude and frequency of triggered and induced seismicity resulting from mine flooding. A thorough understanding of the interaction between flooding and seismicity will allow the impact of mine flooding on safety to be determined. In particular, the maximum credible earthquake size resulting from the flooding of deep gold mines in South Africa needs to be determined. The identified risks will in turn allow appropriate mitigating strategies to be developed. Such strategies will influence South African mine closure policies.

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