SEISMIC RISKS POSED BY MINE FLOODING

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ABSTRACT

Many South African gold mines will flood when they close, as the groundwater will gradually fill the mining voids. Preliminary investigations have shown that flooding of mines can generate increased levels of seismicity. Examples are given that illustrate some of the characteristic differences between fluid-induced seismic events and mining-induced events.

This paper aims to create awareness that fluid-induced seismicity will become increasingly important in South Africa when closed mines are allowed to flood. Such flooding-induced seismicity can have significant environmental, social and economic consequences, and may endanger neighbouring mines and surface communities.

While fluid-induced seismicity has been observed in other settings (e.g. filling of dams, oil-well stimulation 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 to contain flooding.

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.

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. Decades later, once the ore has been extracted and the mine closes, the groundwater is allowed to fill the mine. The water will then fill the mining voids from the deepest underground levels to the height of the groundwater rest level (which could be the Earth's surface).

Flooding of South Africa's worked-out deep gold mines 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). 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 therefore 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 have significant environmental, social and economic consequences, and may endanger neighbouring mines and surface communities.

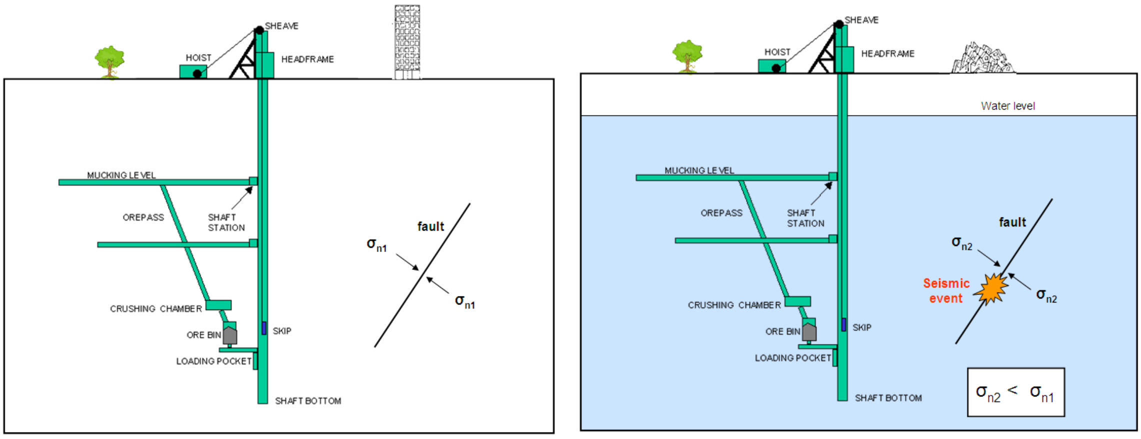

Figure 1. Mine flooding reduces the clamping forces (σ_n) on a fault (right picture) compared to a dry mine (left picture) resulting in mine tremors

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 paper begins with some historical examples of fluid-induced seismicity in non-mining settings. Next, the underlying mechanism for fault slip in the presence of water is 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 given. Finally, the seismic risks associated with mine flooding are highlighted, along with the implications for the South African Government.

2 Historical Evidence for Fluid-induced Seismicity

Fluid-induced seismicity is a commonly observed phenomenon where fluids enter cracks and generate pore pressures that are high enough to cause the cracks to slip. In some cases, the pore pressures may be so high that even intact rocks are cracked open. In this case new fractures will be created through a process known as "hydrofracturing" (Shapiro et al., 2005).

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 (Gahalaut et al., 2007), 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. 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).

Some case histories of fluid-induced seismicity are briefly described here.

2.1 Wellbore Injection

2.1.1 Rocky Mountain Arsenal, Denver, Colorado

In 1967, three large earthquakes (magnitude 5.0 to 5.5) shook the city of Denver, Colorado, USA (Healy et al., 1968). These large earthquakes followed a spate of minor, but continual, seismic activity that had begun in April of 1962. No such concentrated seismic activity, or large earthquakes, had occurred in the area previously. It turns out that the U.S. Army had begun pumping contaminated fluids into a deep rock reservoir at the Rocky Mountain Arsenal, northeast of Denver, in March of 1962.

In 1961, a 3671 m deep disposal well was completed by the U.S. Army at the Rocky Mountain Arsenal. The well was drilled through some 3.6 km of sub-horizontal sedimentary strata of the Denver Basin into the underlying Precambrian crystalline basement. It was the intention of the U.S. Army to pump waste fluids from chemical manufacturing operations into the basement rocks as a permanent disposal technique. 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.

At the start of the Rocky Mountain Arsenal fluid injection programme, two seismic monitoring stations were active in the Denver area. Both stations began to record seismic activity from the region northeast of Denver about a month after fluid injection began. After the initial seismicity had been recorded by these two stations, the U.S. Geological Survey established a number of additional temporary seismograph stations in the vicinity of the Rocky Mountain Arsenal. 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). Furthermore, Figure 3 shows a striking correlation between wellbore pressure and earthquake frequency and that the seismicity continued for almost two years after fluid injection was stopped in early 1966.

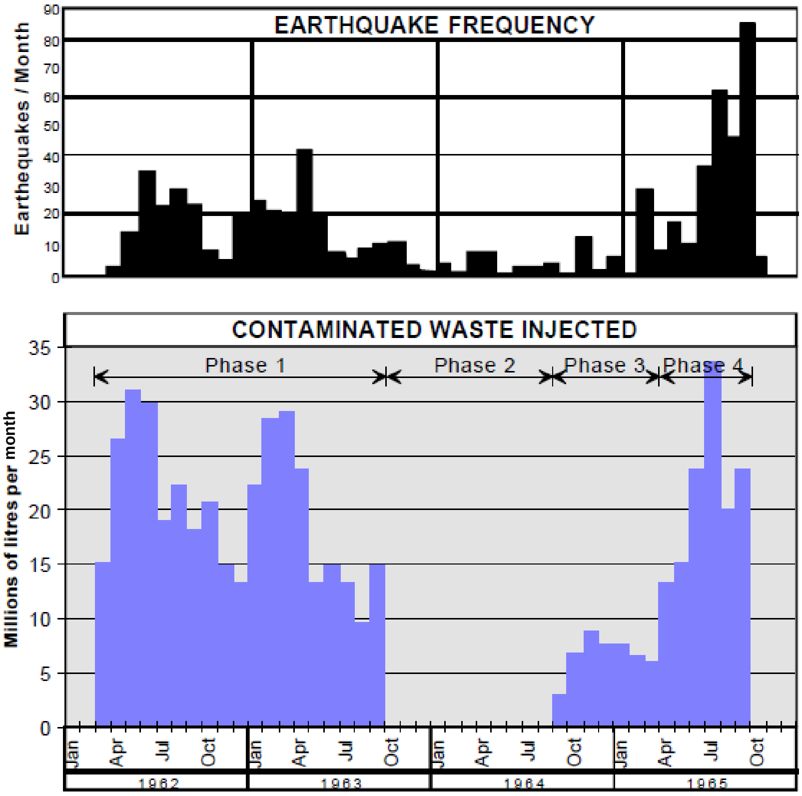

Figure 2. Comparison between Denver earthquake activity and the four phases of fluid injection at the Rocky Mountain Arsenal. Phase 1: 21 Ml/month (active pumping). Phase 2: no pumping. Phase 3: 7.5 Ml/month (gravity flow only). Phase 4: 17.5 Ml/month (active pumping) (after Healy et al., 1968)

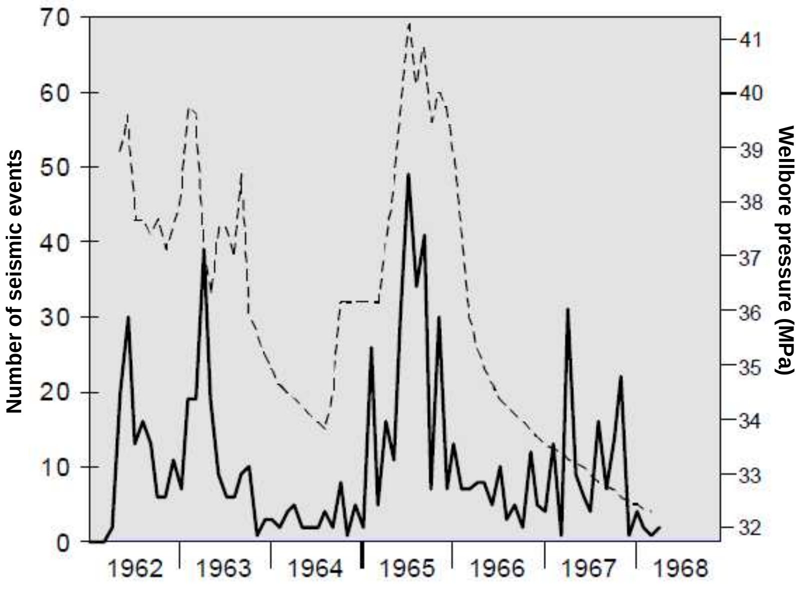

Figure 3. Monthly seismicity (solid line) compared to bottom-hole pressures (dashed line) at the Rocky Mountain Arsenal (after Healy et al., 1968)

Sixty-two seismic events were accurately located over a two-month period near the end of the injection programme in the vicinity of the disposal well (Figure 4).

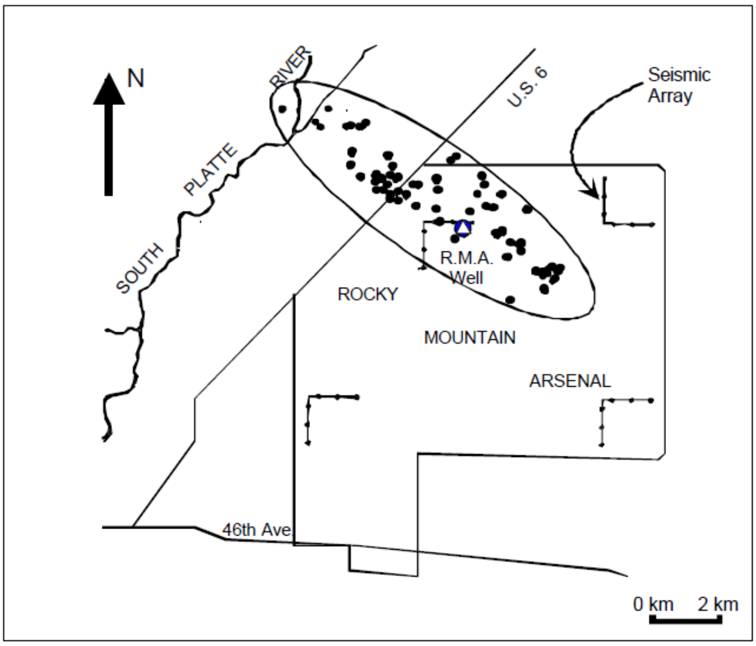

Figure 4. Epicentres of 62 earthquakes recorded over a 2-month period near the RMA well (after Healy et al., 1968)

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. All three large events (and their aftershocks) occurred within the zone of previous activity (Figure 5). A study of the earthquake history prior to the Rocky Mountain Arsenal disposal programme revealed that there was “no evidence of seismic activity before 1962 similar to the earthquakes that have occurred since 1962” (Healy et al., 1968).

Healy et al. (1968) concluded that it was likely that the cause of the Denver earthquakes was a regional stress field of tectonic origin. The injection of fluids into the basement rocks through the Rocky Mountain Arsenal disposal well triggered the release of stored tectonic strain energy resulting in the observed seismic activity. Seismic activity ceased shortly after the earthquakes of late 1967 and no further fluid injection was undertaken at the Rocky Mountain Arsenal. The correlation between fluid injection and seismic activity in both time and space was striking and lead to a major interest in the relationship between fluids and seismic activity.

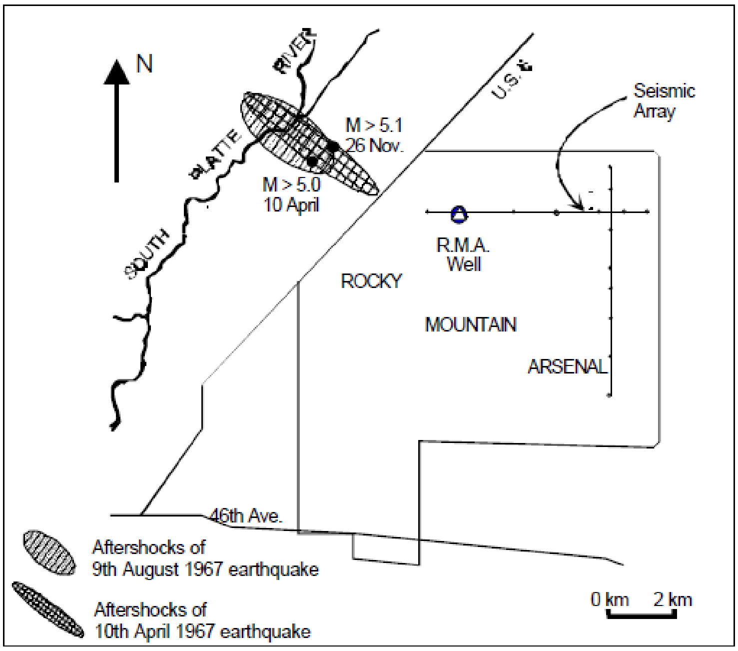

Figure 5. Locations of two of the three large earthquakes and their aftershocks recorded near the RMA well (after Healy et al., 1968)

2.1.2 Rangeley Oil Field, Colorado

The Rangely oil field (Gibbs et al., 1973; Raleigh et al., 1976) is situated in Rio Blanco County, Colorado and completely surrounds the town of Rangely near the border of Utah (Figure 6). Oil was discovered 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.

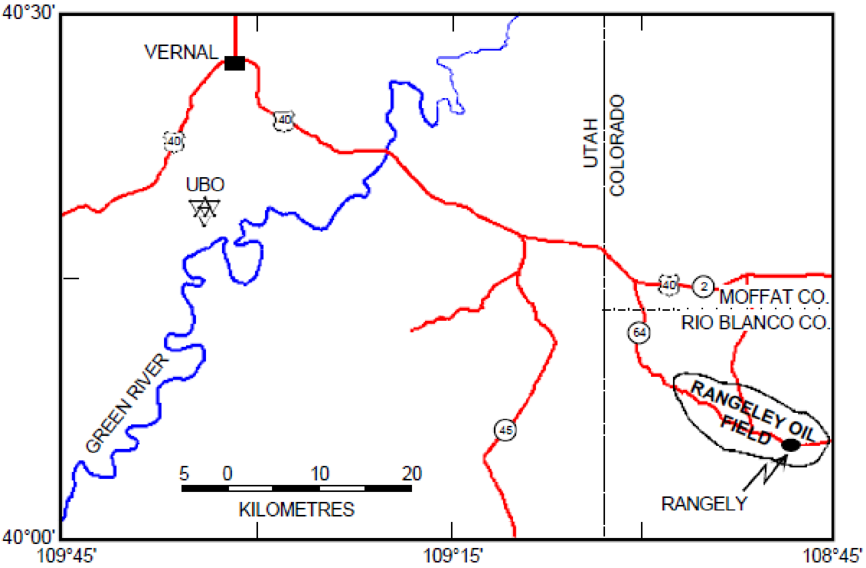

Figure 6. Location map showing the Rangely oil field (from Gibbs et al., 1973)

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 1965, 97 wells had been converted to injection wells and by September 1969 water was being injected into a total of 202 wells. During secondary oil production by fluid injection it was observed that seismic activity in the Rangely area appeared to increase (Scholz, 1990). A large number of seismic events was identified as originating from the Rangely oil field (Figure 7). Much of the seismicity coincided with the southern extent of a fault that cuts through the centre of the field.

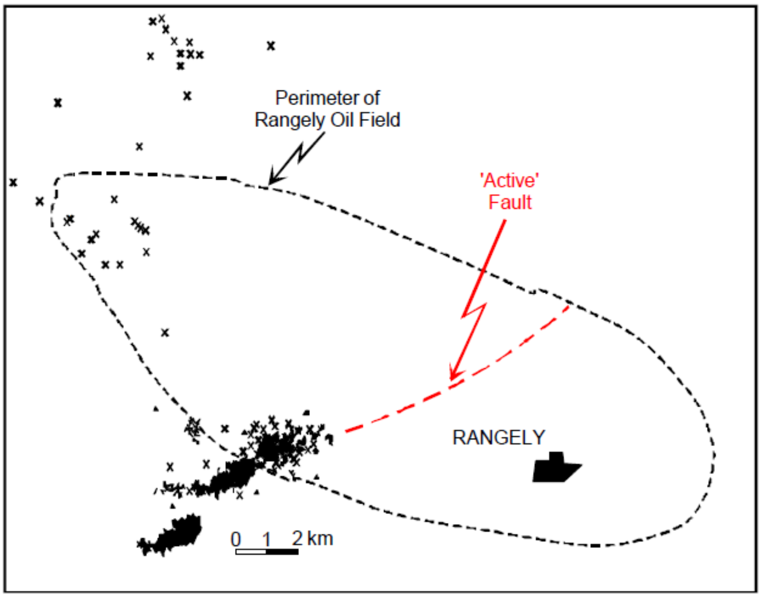

Figure 7. Earthquakes located at Rangely from October 1969 to November 1970

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. It was concluded that if the fluid injection rate increased then the amount of recorded seismic activity also increased. During a subsequent fluid-injection experiment using four wellbores the largest event recorded was magnitude 3.1. All hypocentres located along a vertical zone trending roughly parallel to the fault identified in the field (Figure 8).

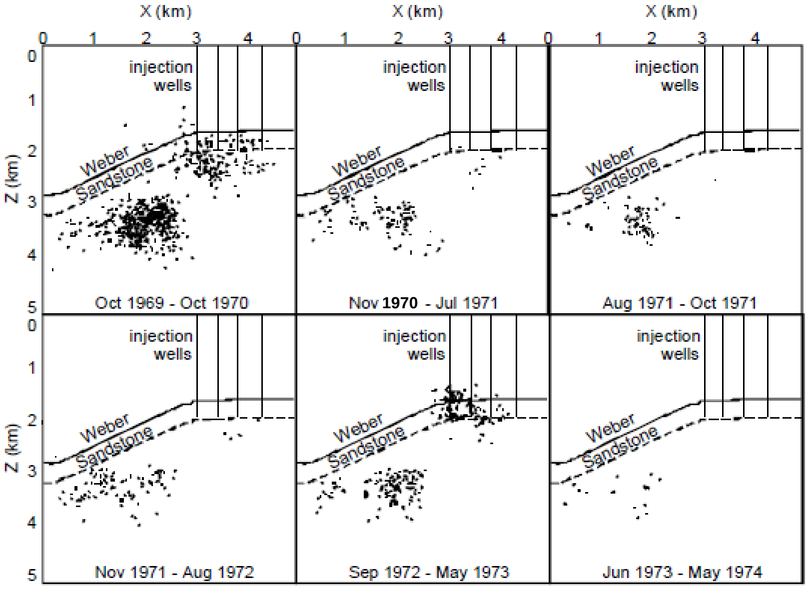

Figure 8. Vertical sections showing earthquake locations over time (from Raleigh et al., 1976)

2.1.3 Matsushiro Experiment

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 being reported (Ohtake, 1974).

Dedicated seismic monitoring of the Matsushiro earthquake region was undertaken for four weeks prior to the initiation of the fluid injection experiment. Dedicated seismic monitoring ceased on 9 March 1970, six weeks after the fluid injection programme had terminated. Unusual seismic activity was first recorded at a distance of between 2 km and 4 km from the wellbore injection locality some nine days after fluid injection had begun. On 25 January 1970 a magnitude 2.8 seismic event was recorded.

The seismic activity during the four week period prior to fluid injection showed little systematic distribution and occurred at depths in excess of 3.5 km. After fluid injection was initiated, events appeared to localise along the projected fault surface and were observed to occur at depths ranging from the injection point and below. The time delay between the initiation of fluid injection and the first recorded seismic activity was nine days. Ohtake (1974) argued that it took time to saturate the fault surface and it was necessary to affect regions of the faulted rock mass that were susceptible to instability. A time migration of seismicity was observed downdip from the injection point. After injection ceased, the seismic trends were observed to revert to those recorded prior to the experiment.

2.2 Dam Impoundment

Numerous examples of earthquake activity associated with the filling (impoundment) of man-made lakes behind engineered dams exist. One of the most devastating of these 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. Two examples of seismicity associated with reservoir filling are briefly discussed here.

2.2.1 Malpasset Dam

The Malpasset Dam in France, which was completed in 1954, catastrophically failed on 2 December 1969 (Jaeger, 1979). 421 people were killed as a result of the collapse of the 61 m high dam wall. Subsequent investigations into the catastrophe found that the design of the dam was not at fault. It was failure of the rock foundation that had initiated the collapse. Two major fault surfaces were identified in the rock of the dam wall foundation, however, tests on the fill material from these faults indicated friction angles between 45° and 60°. It was considered that this was too high to allow sliding along the fault planes.

Subsequent investigations into the Malpasset tragedy identified the important role that water had played in the collapse of the dam. It was deduced that the head of water contained by the dam was sufficient to cause water to flow into fractures in the bed rock at the toe of the dam wall. The water pressure was sufficient to overcome the downward pressure of the mass of the dam wall, resulting in tensile vertical stresses in the bed rock forming the foundation of the dam wall. The water restrained by the dam wall forced the dam to lean downstream over the toe of the wall leading to the ultimate failure of the foundation and resulting in the total collapse of the dam itself.

The Malpasset Dam failure was one of the first incidents that indicated the magnitude of the effect that water could have on rock.

2.2.2 Vajont Dam

The Vajont Dam in Italy, which was completed in 1960, over-spilt on the 9 October 1963 resulting in 2600 deaths (Jaeger, 1979). The 265 m high thin wall concrete arch dam was left undamaged by the incident. Investigations into the disaster found that 240 million cubic metres of rock and earth comprising a portion of the bank of the dammed lake slid into the water at a high velocity causing much of the water in the lake to be ejected over the dam wall, resulting in devastation downstream.

Further investigations revealed that the slip surface along the base of the slide was a pre-existing natural fissure. During impounding of the dam the water pressure became sufficiently high to force water into this fissure. Ultimately the induced tension across the fissure was large enough to allow the over-lying material to slide into the lake with devastating consequences.

2.3 In-Mine Fluid Injection

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

The aim was to induce shear slip on existing fault surfaces in mines that had the potential to produce large (more than magnitude 3) seismic events. By inducing numerous smaller events (magnitude 0 to 1) through water injection it was hoped that stored strain energy due to mining could 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 drilled to intersect 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 magnitude greater than zero were recorded. However, numerous micro-seismic events (magnitude less than zero) that could confidently be claimed to have been induced by fluid injection were induced (Figure 10).

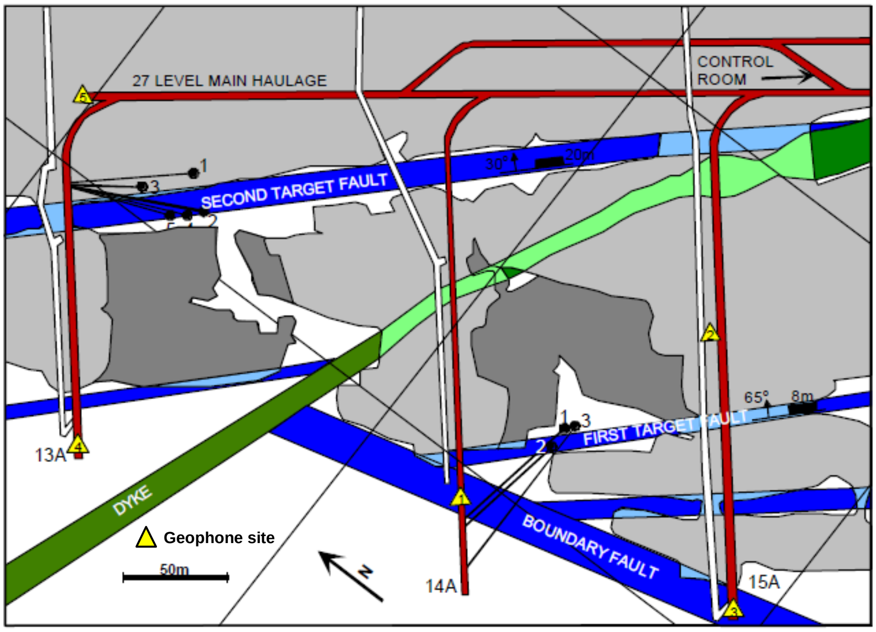

Figure 9. Plan of a fluid injection field site showing wellbores drilled onto two target faults (from Lightfoot and Goldbach, 1995)

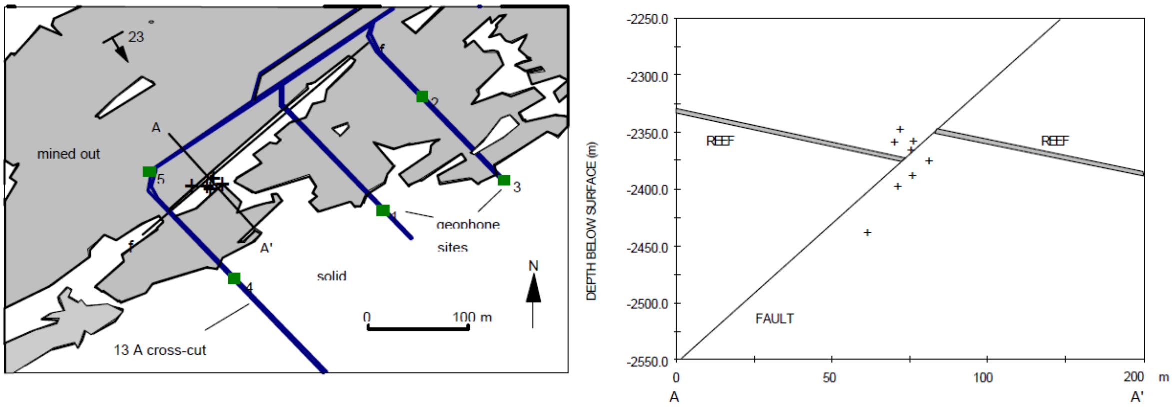

Figure 10. Locations of induced micro-seismic events (+ symbols) due to fluid injection in plan (left) and in section (right) (from Lightfoot and Goldbach, 1995)

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 Mechanics of Fault Slip

The mechanics governing the potential for slip on a fault surface can be considered in terms of a Mohr-Coulomb failure criterion. This criterion assumes the fault surface to be planar and the shear strength of the fault is described in terms of the ambient stress field and the cohesive and frictional strength of the discontinuity. The ambient stress state acting on the fault can be altered by the presence of a fluid pressure acting in the fault surface void. This change in stress state can be described in terms of the effective stress concept.

3.1 Fault Strength

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. The limiting case for slip is when the shear strength of the fault equals the shear stress acting parallel to it. A fault will thus slip, if

$$\sigma_S \geq \tau_S \qquad (1)$$

where

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

For a fault in equilibrium (stable), the shear stress (σ_s) acting parallel to the surface must be less than the shear strength (τ_s). If a fault is considered to be a planar discontinuity in a rock mass, then the resistance to slip along the 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.

$$\tau_s = c_0 + \sigma_n \tan\phi \qquad (2)$$

where
σ_n is the normal stress acting on the fault surface
ϕ is the friction angle of the fault surface
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 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).

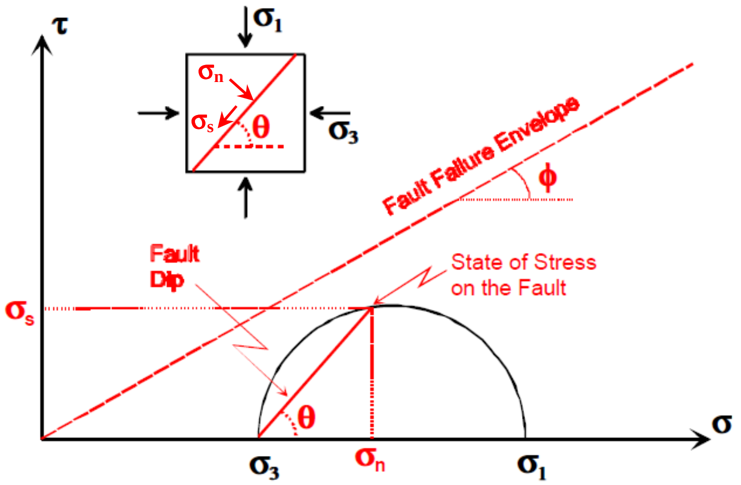

Figure 11. State of stress in a rock mass represented on a Mohr-Coulomb diagram

3.1 Effective Stress

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)

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

where

σ_{pp} is the water pressure

Hence, 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). 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.

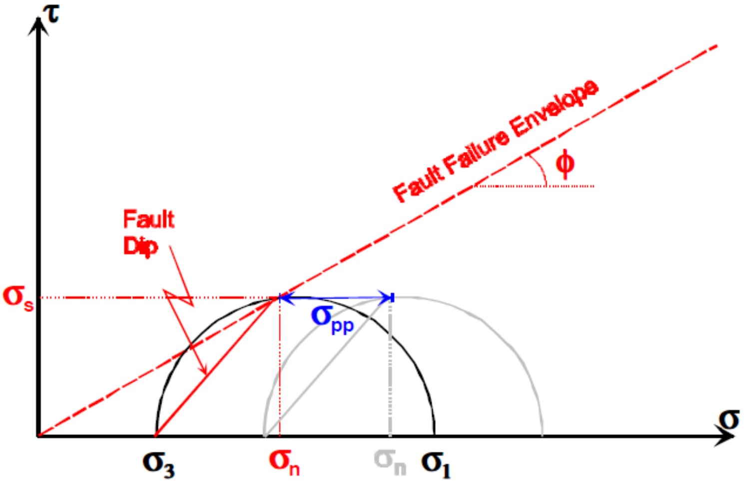

Figure 12. State of stress on a fault surface after the introduction of a pore pressure σ_{pp}

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, hydrolysis and dissolution – 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.

4 Flooding of South African Mines: Uniqueness

If fluid-induced seismicity has been observed and studied globally in a number of non-mining settings, what makes seismicity associated with mine flooding so important?

The answer is that, although the learning from oil-well stimulation and dam impoundment will indeed be relevant, seismicity associated with flooding of mines is probably different 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

This section reports on some of the characteristic differences that have been observed with fluid-induced seismicity compared to seismicity associated with normal deep-level mining operations. The observations come from a deep-level South African gold mine that had installed a seismic system to monitor their mining-induced seismicity.

While monitoring the mining-induced seismicity in a deep level production area of a mine, additional seismic activity was noticed in an adjacent worked-out part of the mine that was being allowed to flood. A plan of the mine is shown in Figure 13.

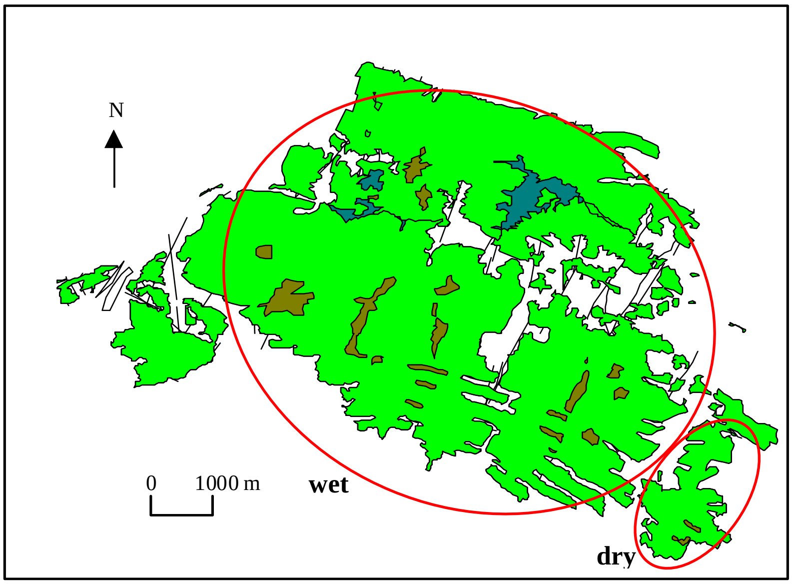

Figure 13. Mine plan showing "dry" production area and "wet" flooding area

5.1 Spatio-temporal analysis

Figures 14 and 15 show the seismicity that was recorded over a 5-year period in the "dry" production area and the "wet" flooding area, respectively.

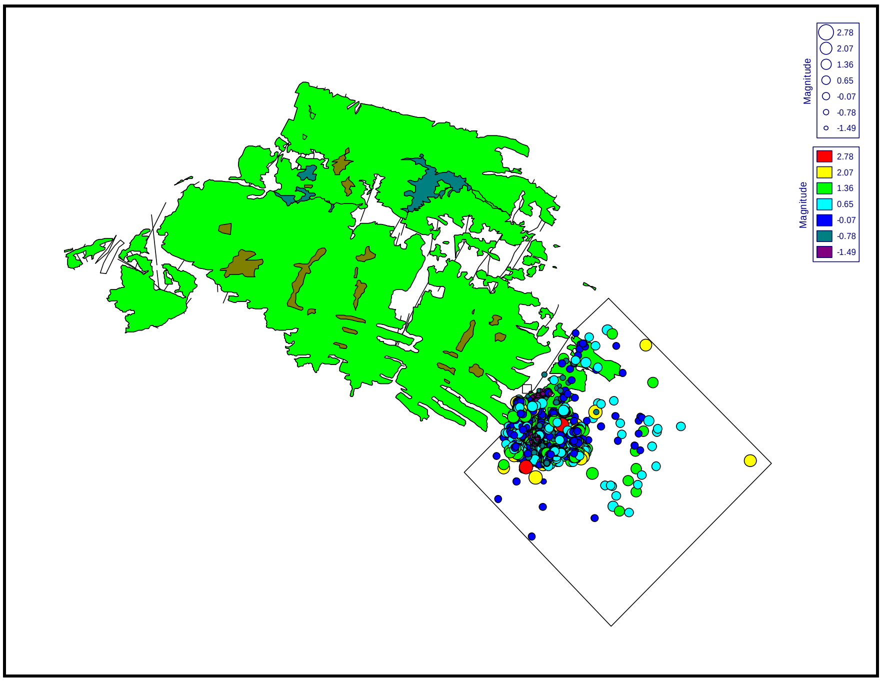

Figure 14. Seismicity recorded in the “dry” production area

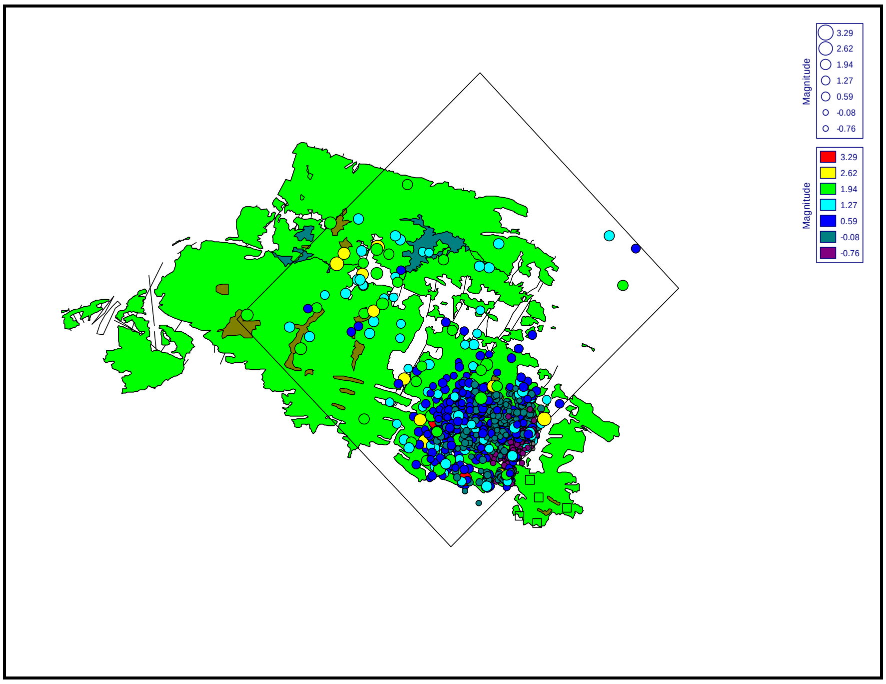

Figure 15. Seismicity recorded in the “wet” flooding area

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.

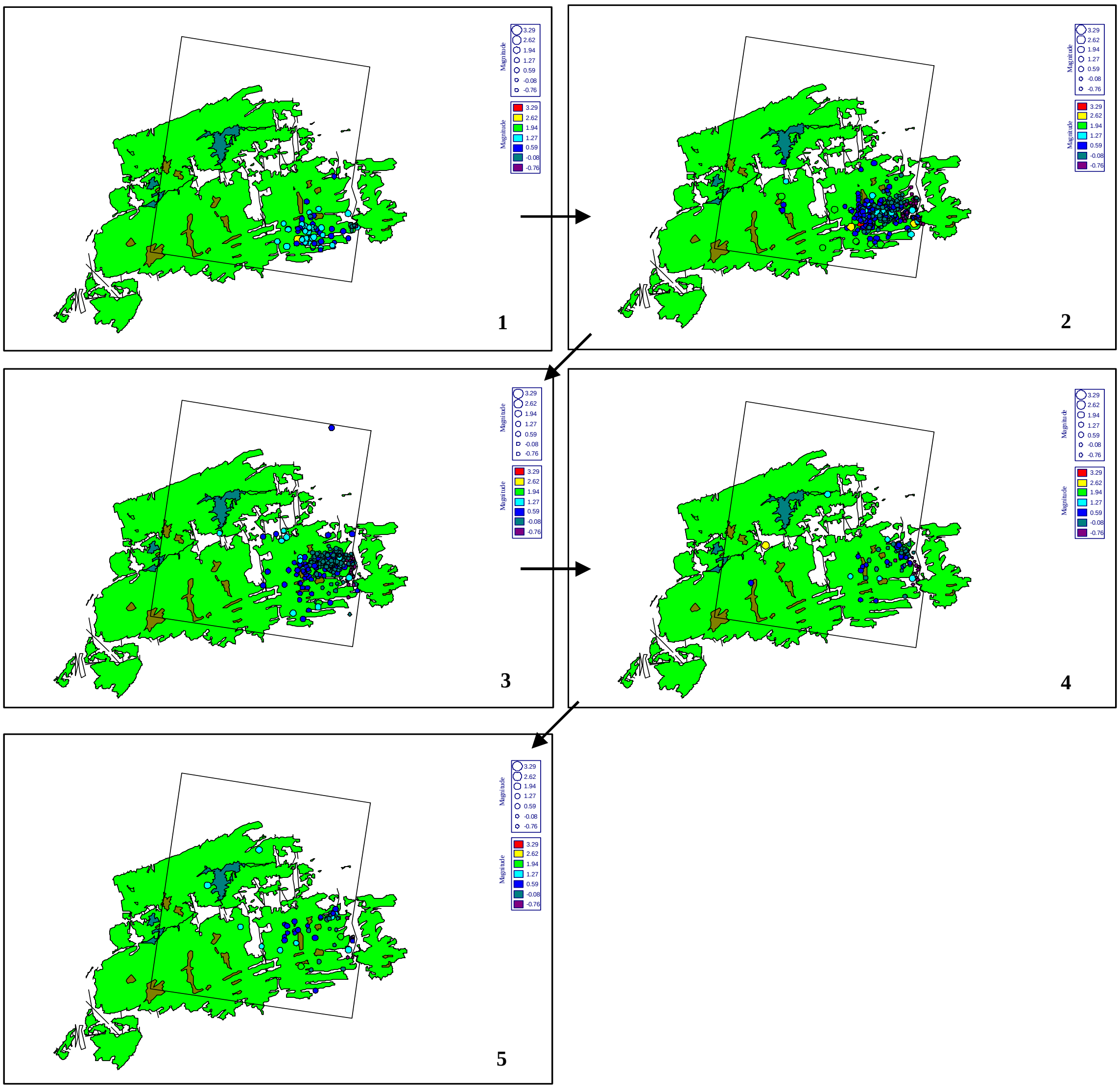

Figure 16. Seismicity recorded in the "wet" flooding area over an 18-month period in 100-day snapshots

A time history graph of the seismic events shows an almost exponential 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. Similar trends are observed when one compares the cumulative time histories of seismic energy and seismic moment for events which occurred in the wet flooding area and the dry mining area (Figures 18 and 19). In all cases an unusually rapid increase in seismic parameter is observed between September 2000 and February 2002 in the flooding area.

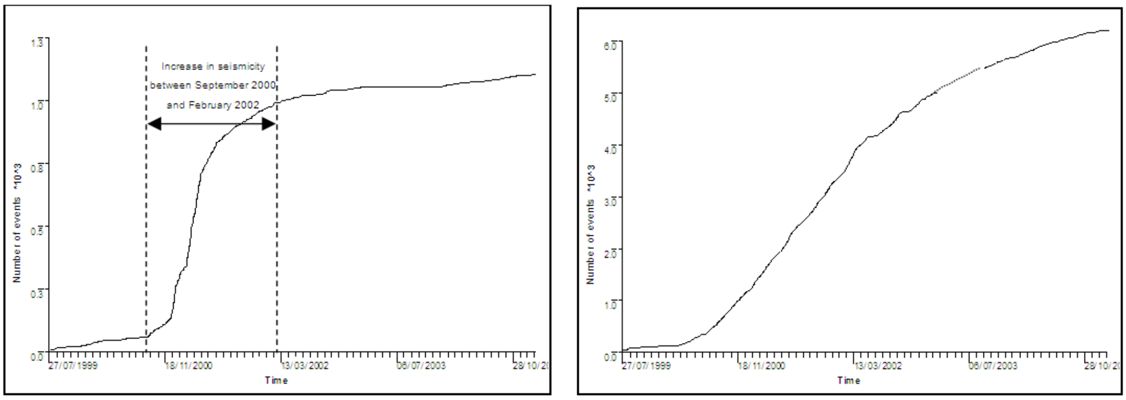

Figure 17. Time history of seismicity recorded in the wet flooding area (left) vs. the dry mining area (right)

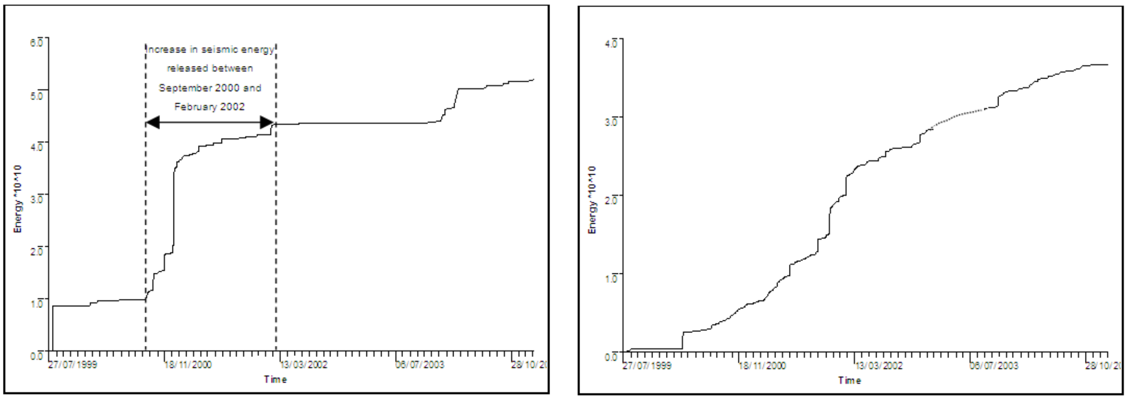

Figure 18. Time history of seismic energy released in the wet flooding area (left) vs. the dry mining area (right)

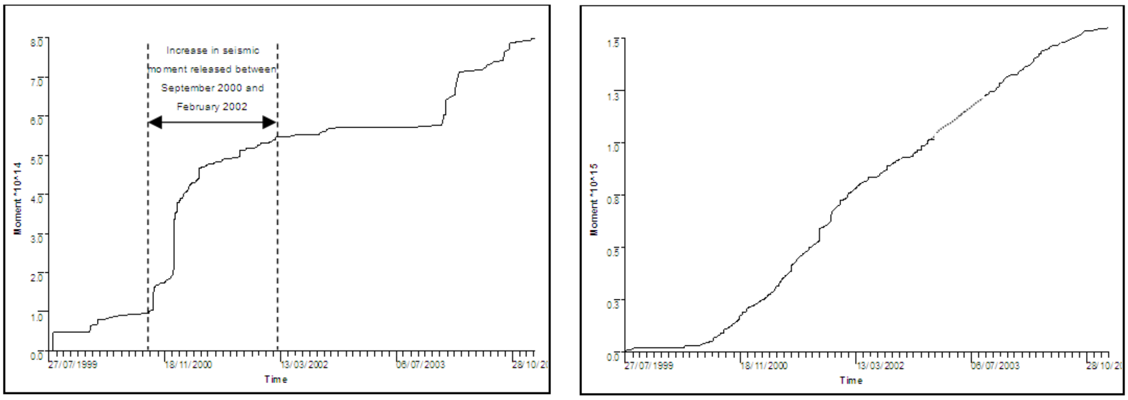

Figure 19. Time history of seismic moment released in the wet flooding area (left) vs. the dry mining area (right)

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 19). The diurnal distribution of these events shows that they also occurred randomly throughout the day.

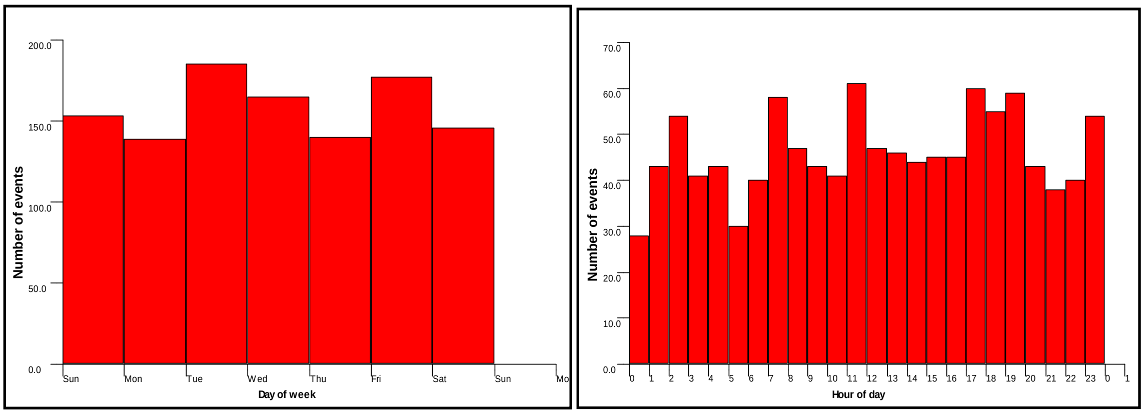

Figure 19. Daily (left) and diurnal (right) event distributions of the seismic events which located in the wet flooding area

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 20 shows relatively few seismic events occurred on Saturdays and Sundays when 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 20 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.

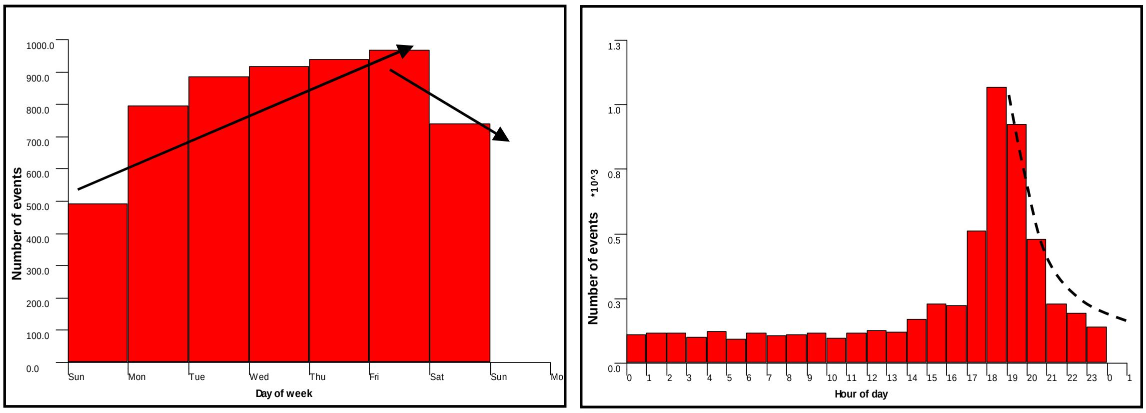

Figure 20. Daily (left) and diurnal (right) event distributions of the seismic events which located in the dry mining area

It became clear that the seismicity in the wet area exhibited distinctly different patterns to that in the dry mining area. To what degree were the observed seismic patterns associated with the flooding? This question is addressed in the next section.

5.2 Correlation between seismicity and flooding

Figure 21 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 21 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. The increase in seismicity between September 2000 and February 2002 was previously observed in the cumulative time histories shown in Figures 17 to 19.

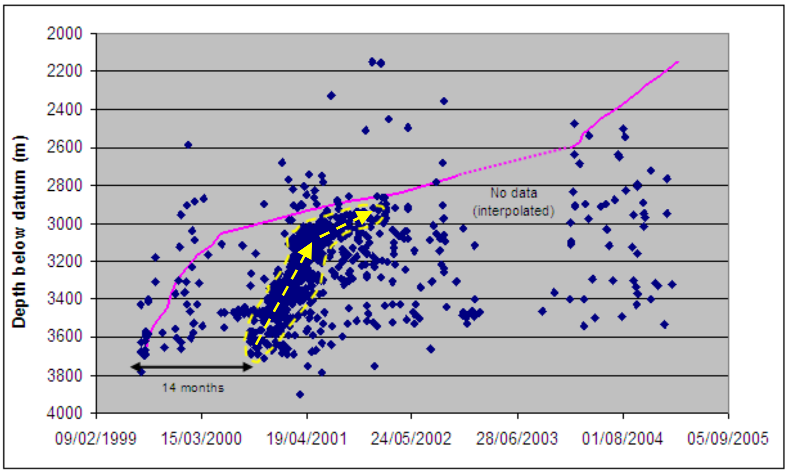

Figure 21. Elevation of water level (solid line) and depth of seismic event locations (diamond symbols) in the flooding area. Note the upwards migration of a cluster of seismic events (dashed line) between September 2000 and February 2002.

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.

A delay in the onset of the seismicity is commonly observed in dam impoundment. As water flows into existing fractures into the rock mass below the 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. 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 21). 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. Delays between the start of flooding and the onset of fluid-induced seismicity were also observed at the Rocky Mountain Arsenal and at the Matsushiro experiment. However, there are probably other complex processes involved, which would have contributed to the delay, such as viscous time-dependent effects of the rock mass.

5.3 Maximum Magnitude of Seismicity associated with Flooding

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, 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.

It is noteworthy that:

- the largest seismic event in the flooding area occurred during the period of intense seismic activity between September 2000 and February 2002; and
- despite the flooding area having been mined out long ago, it generated bigger seismic events than the neighbouring mining area.

6 Seismic Risks and Consequences of Mine Flooding

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 severe structural damage to the town (Figure 22). 3200 miners were evacuated under difficult circumstances. 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?"*

Following the Stilfontein earthquake, the Department of Minerals and Energy (DME) commissioned a Section 60 investigation into the risks to miners, mines, and the public associated with large seismic events in gold mining districts (Durrheim et al., 2007). Later the President of South Africa ordered an industry audit of mine safety in October 2007 in order to address the risks associated with mining as approximately 200 people continue to die in South African mines each year. 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.

Figure 22. Damage to buildings in Stilfontein following a magnitude 5.3 mining-related earthquake (from Durrheim et al., 2007)

6.1 Economic Impact of Large Seismic Events

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.

A number of South African gold mines are currently each paying between R 6 million and R 8 million per month to pump water out from underground (Business Report, 2005; The Star, 2005; Sheqafrica.com, 2009; Miningmx, 2009). Pumping is necessary to prevent the flow of water from mines at a higher location within the mining areas to lower-lying operational mines.

Once mines close, the State may have to bear the expected (indefinite) monthly pumping cost of R 6 million to 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. The Stilfontein earthquake cost about R 500 million in insured damage.

6.2 Impact of Mine Flooding on Safety

The Central Rand Gold mining company has recently restarted gold mining activities beneath Johannesburg (Mining Weekly Daily News, 2008a). *Will Johannesburg experience an earthquake the size of the Stilfontein event once Central Rand Gold has closed and the mine floods?* No-one knows. But, if it does, the consequences could be severe. Figure 23 shows the damage caused by a magnitude 5.2 mining-related earthquake to a block of flats in Welkom on 8 December 1976.

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. It is therefore in the national interest that the risks associated with fluid-induced seismicity be understood before many South African mines will close.

Figure 23. Damage to a block of flats in Welkom following a magnitude 5.2 mining-related earthquake (no fatalities)

Mine flooding is also very important for current mining operations, because one of the big risks is that a seismic event may damage a water barrier pillar between a flooded mine or section and an adjacent working operation. A barrier pillar failure could potentially be the greatest disaster ever to occur in South Africa's mining history.

7 Implications for the South African Government

The risks associated with fluid-induced seismicity need to be quantified now. Funding needs to be made available for research that 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 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, 2008b; Mining Weekly Daily News, 2008c). 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 pore pressures resulting from the underground storage of such gases could be large enough to liquefy the gases, which could cause faults to slip and generate seismic events in a similar manner to water (Sminchak et al., 2002). 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, 2008). 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 was 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 have significant environmental, social and economic consequences, and may endanger neighbouring mines and surface communities.

While fluid-induced seismicity has been observed globally in other settings (e.g. filling of dams, oil-well stimulation 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 to 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.

It was also noteworthy that the flooded region generated larger magnitude seismic events (M_{max}=3.3) than the neighbouring dry deep-level mining (M_{max}=2.8). The largest events occurred under 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 contend 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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