6. Subsurface stress modelling in mining areas – defining zones of seismic potential

(by D. Birch)

The purpose of this investigation was to model the structural trends within the Central Rand Basin using an assumed pre-mining stress model in order to identify zones in the basin that are more “seismicity-prone” than others. The method was to build 3D models representing the different structure orientations with respect to the different orientations of the tabular mine void across the basin and analyse the patterns of shear displacement. The mechanism for triggering instability in the model is an applied pore pressure, representing the flooding that has taken place in the mine void. A detailed map of the structural geology together with a review of the structural setting formed the basis for this study. The 12 station seismograph network which spans the Central Rand Basin provided locations of seismic events with which to validate the results of our model.

6.1 Structural setting

Mining activities allow for rare insight into the crustal state especially when depths reach 3.5 km as in the case of ERPM. A detailed structural geology map based on underground observations is an example of important information that can be extracted (Figure 10). The map shows all the dykes and faults together with their dislocation ages and some characteristics (normal, wrench, thrust etc.) overlain onto the reef contours.

In assessing this map, all the structures could be grouped into four distinct orientations. These orientations were later modelled to ascertain each ones propensity to slip. According to these orientations, labelled 1 to 4, the map can be
divided into two parts. From DRD in the West up to Robinson Deep, orientations 1 and 4 appear to dominate and from City Deep to ERPM in the East orientations 2 and 3 occur most frequently (Figure 11). The dip direction of the mining also changes as it follows the folded reef, varying between approximately 140° to 220°.

Mining followed the reef in the Central Rand Basin which dipped to the south at roughly 30°. Over a century of mining, which started in 1886, has left behind a vacant slot in the earth’s crust extending from the surface down to a maximum depth of 3500 m, and extending some 50 km from east to west (see Figures 10, 11). The hypothesis for this study is that this particular geometry and left-lateral wrenching caused by a northeast/southwest basin-wide compression will cause structures of a certain orientation to be more prone to movement than others. Identifying these structures is important to understanding the risk that flooding might pose.
Figure 10. Structural geology mapped underground in the mines (Pretorius, circa 1970).

Figure 11. Grouping dykes and faults according to approximate orientation.
6.2 Pre-mining stress model

The selected pre-mining stress state was based on the work by Handley (2012), represented in Figures 4 and 5, which proposes a crustal stress model for Southern Africa based on a collection of stress measurement data collected by Stacey and Wesseloo (1998a). The 3DEC pre-mining stress model was defined as follows, where $z$ is depth in metres:

$$\sigma_V = 0.027z \quad \text{(MPa)}$$

$$\sigma_{H1} = \sigma_{H2} = 3.5 + 0.02z \quad \text{(MPa)}$$

The vertical stress has been shown to be fairly predictable, being close to the weight of the overburden (McGarr, Spottiswoode and Gay, 1975; McGarr and Gay, 1978; Gay, 1979). The maximum principal stress is horizontal above a depth of 500 m and vertical below that. This crossover is identified and discussed by McGarr and Gay (1978). Although the aforementioned authors have defined two different horizontal stresses, they are equal here for two reasons: firstly, there is too little measured data (only one measurement in the region; Pallister, 1969); and secondly, to avoid directional bias in the geomechanical model.

6.2 Method

The process of defining zones of seismic potential is a first step towards the mitigation of the seismic risk, since knowledge of high risk areas could lead to better city planning and readiness of emergency services. The approach presented in this report was based on results from the 3D models and a structural geology map. The models that were built as contain unavoidable assumptions, thus, providing only qualitative results.

Three models with a simplified mined out void were built. Each model contained the same four discontinuities (identified in section 2) dipping vertically and intersecting
the void and each other. The only difference between the three was the orientation of the 30°-dipping void which varied in dip-direction from 142° (DRD) to 180° (City Deep) to 218° (ERPM).

Based on the shear displacements that formed on the model discontinuities when the pore pressure was applied, vulnerabilities in each of the models were identified. The distribution of the different structures with various orientations represented on the structural geology map was analysed mine-by-mine to identify areas that may be at risk. A plot of relocated seismic events that were recorded between 25 March 2010 and 30 June 2012 was used for comparison with the results.

6.3 Results

It is clear from Figures 12 to 14 that the features “most perpendicular” to the direction of dip experience most of the shear displacement in the model and those parallel to the mining advance experience very little. This illustrates the strong dependence on the geometrical configuration, which is the central theme to this study. The propensity to slip is determined by the relative orientation of the feature with the mining void.

The results from the models were combined with figure 10 in an attempt to find areas with a high potential for instability (see Figure 15).
Figure 12. Shear displacement magnitude contours on features intersecting the southerly dipping (180°) mine, representative of the Robinson Deep to City Deep mines at the centre of the Central Rand Basin.

Figure 13. Shear displacement magnitude contours on features intersecting the south-easterly dipping (142°) mine, representative of the DRD mine in the western section of the Central Rand Basin.
Figure 14. Shear displacement magnitude contours on features intersecting the south-westerly dipping (218°) mine, representative of ERPM in the eastern section of the Central Rand Basin.
Figure 15. The structural geology map was divided according to the change in dip direction of the mine void, illustrated by the blue arrows. Features that are likely to slip according to their orientation with respect to the mine void are highlighted in green. Some of these were given names and those names are listed in the blocks.
6.3 Comparison with observed seismicity patterns

A network of 12 seismograph stations has been in operation in the CRB since March 2010, providing valuable seismic data. All the events recorded by this network up to the end of October 2012 were relocated using the double difference earthquake location algorithm called HypoDD of Waldhauser & Ellsworth (2000).

The network has a very wide longitudinal coverage (~50 km) as opposed to latitudinal (~15 km) due to the shape of the basin. This has an adverse effect on the latitudinal constraint of the event locations. The planar arrangement of a surface network hinders depth determination. A more accurate velocity model is also still to be developed, which may shift locations slightly. Current longitude and latitude location errors are in the range of 500 m. Although 12 stations over such a small area seems dense, depth determination without the use of additional phase identification requires that the nearest station be a distance away from the epicentre that is similar to the depth of the event. Due to the shallow nature of the seismicity (1 – 3 km deep) this rarely happens for the larger events that are observed, making depth determination troublesome.

Nevertheless, some spatial patterns in the relocated seismicity were observed. The first observation is that almost all of the epicentres fall within mine boundaries. This merely indicates that the presence of the abandoned mines is a controlling factor. In other words, the removal of material underground has created instability in the rock mass that is being exploited by the water.

The distribution of seismic events appears to be clustered, as highlighted in Figure 16, in the areas to the west and in the north of ERPM, the southern parts of City Deep and Robinson Deep and tracing across ERPM with a northwest/southeast alignment. This lineament at ERPM is also where the largest events have been observed.

The overall distribution of seismicity agrees well with the distribution of vulnerable features identified through modelling. This suggests that the position of the mine void
within the shallow crust is indeed a controlling factor in the location of features that are most likely to fail and seismicity is being controlled by this rather than tectonic stresses. The fact that this could be demonstrated with a simple model is also an indication of the uniform distribution of crustal stress within the basin.
Figure 16. Structural geology map with the locations of the seismograph stations and relocated seismic events in the Central Rand Basin. Shaded areas highlight clusters of seismic activity. These agree well with the distribution of potentially unstable features in Figure 15.
6.4 Conclusions

Mining of the Central Rand Goldfields had mostly ceased by the close of the 1970’s. By 2002 there was only one mine in operation. It is believed that residual stresses left over from mining are being exploited by the water. Pore pressure changes in the fractured rock mass are causing previously stable features to become unstable. The largest seismic events will most likely occur on the longest pre-existing geological feature, such as a fault or dyke. All of these features were diligently mapped underground by Pretorius (Circa, 1970).

A tectonosedimentary model by Stewart et al. (2004) characterizes the structural model of the basin as left-lateral wrenching. Structures associated with this (left-lateral strike-slip faults) are exclusively indicated in the region of ERPM on the structural geology map (Figure 10). This might be the reason for the largest events occurring there, since the area is obviously prone to failure caused by pre-existing tectonic stresses. Another reason might be that ERPM was the last mine to stop pumping and, therefore, has had less time to release residual mining-induced stresses.

Results from the 3D models showed an average shear displacement of approximately 5 cm and a maximum 12 cm. Joint shear stresses up to 60 MPa were induced by the removal of material to form the void. The model produced stress and strain conditions comparable to those observed underground and demonstrated the strong dependence of an intersecting feature’s propensity to slip on its relative orientation with respect to the mine void. Strong assumptions such as; a uniform the rock mass, shape of the mine void and discontinuities, were unavoidable. Despite this, there was good agreement between the spatial distribution of seismicity and the positions of potentially unstable features, which suggests two possibilities:
• Seismicity is being controlled by stresses induced by the shape and orientation of the mined-out reef on intersecting geology rather than tectonic stresses.

• The shallow crust can be described by a homogenous material and uniform stress model.

Earthquakes are consistently being recorded in the CRB with some reportedly felt by the public. Although, these have not caused any damage yet, the possibility that any of these features may slip over a very large surface area still remains.

Further analysis on the risk faced by the city of Johannesburg should include higher accuracy locations of seismicity so as to identify any increase in movement on large structures, which might be indicative of a catastrophic seismic event. This can only be achieved together with accurate depth determination. Special attention should be given to the communities of the three areas highlighted in Figure 16 to ensure the readiness of emergency response services in the case of a damaging earthquake.
7. Temporal and spatial variation of seismicity in the Central Rand Basin 2012

(by A. Cichowicz, D. Birch, L. Labuschagne and G. van Aswegen)

The estimation of source parameters allows for the characterization of seismicity triggered by a rising water level in the Central Rand Basin. Relations between source parameters such as stress drop versus seismic moment, seismic energy versus seismic moment and others were calculated. These relationships will aid in the understanding of physical phenomena that occur in the medium due to void flooding.

A study of the spatial variation of seismicity is the one of the main objectives of this investigation. The Central Rand Basin is divided into cells with the number of cells controlled by the level of seismicity. The observed seismicity is analysed to reveal both spatial clustering and scattering across a large area.

Temporal variation of seismicity and trend analysis over long periods allows for the measuring of differences in seismic source parameters over time. Trend analyses between source parameters attempt to spot patterns, revealing any significant changes in the relationships.

7.1 Seismic source parameters

A catalogue of almost 1000 earthquakes was created and the spectral parameters of the events were estimated. Enabling output 2 of the project entitled “Estimation
of Source Parameters" 2011/2012 presents the details of the method used to process waveforms.

A new relation between $M_L$ and $M_w$ was obtained. The relationship $M_w = 0.49 M_L + 0.85$ was estimated using values of $M_L$ from 0.2 to 3.5. Scalar seismic moment varied from $10^{10}$ to $10^{14}$ Nm.

### 7.1.1 Relationships between radiated seismic energy and seismic moments

The relationship between radiated energy and scalar seismic moment is shown in Figure 17. The blue box on the graph schematically marks a range of the parameters obtained for the Central Rand Basin. The graph compares the results from several experiments conducted mostly in mining environments (see figure from Kwiatek et. al., 2012). Lines of constant apparent stress, $\Delta \sigma_{\text{app}}$, are shown as dashed lines. The dependence between seismic moment and radiated energy for different studies show a similar pattern. In the Central Rand Basin area the radiated energy of the seismic events increases with seismic moment. The seismic energy covers a range of about six orders of magnitude.
Figure 17. The relationship between radiated energy and scalar seismic moment for the Central Rand Basin area and comparison with other similar studies - figure from Kwiatek et al., 2012. The blue box on the bottom graph schematically marks range of parameters obtained for the Central Rand Basin. The lines of constant apparent stress $\Delta\sigma_{\text{app}}$ are shown as dashed lines.

The new data confirm that the average $M_{\text{SH}}$ scalar seismic moment is bigger than the $M_{\text{SV}}$ scalar seismic moment. A similar type of relationship is observed between the radiated seismic energies $E_{\text{SH}}$ and $E_{\text{SV}}$. A near surface soil column usually contributes to an increase in the SH-wave amplitude compared to the amplitude of the SV-waves. Therefore, $M_{\text{SH}}$ seismic moment should be higher than the $M_{\text{SV}}$ seismic moment and the radiated seismic energies $E_{\text{SH}}$ also higher than $E_{\text{SV}}$. The correlation coefficients between the estimated values of seismic moments and seismic energies are very high 0.96 and 0.98 respectively.
The range of the SV-wave energy is from $10^3$ to $10^9$ J. The energy of the P-wave is of a similar order compared to that of the SV-wave, but significantly lower than that of the SH-wave. The following two relationships are obtained: $E_p = 0.2 E_{0SH}$ and $E_p = 1.4 E_{0SV}$. The ratio of the total shear wave energy to the total P-wave energy is $(E_{0SH} + E_{0SV}) / E_p = 5.7$. For seismic events involving mainly shearing, the P-wave radiated energy is smaller than the S-wave radiated energy by factor of 10 to 30 (Gibowicz and Kijko, 1994). The observed $(E_{0SH} + E_{0SV})/E_p$ ratio could be attributed to a dominantly shear type of fracture mechanism in the seismic sources of the Central Rand Basin.

### 7.1.2 Relationships between apparent stress drop, static stress drop and seismic moments

The seismic hazard assessment relies heavily on the assumed static stress drop for the largest expected magnitude. Therefore, understanding the relationship between seismic moment and stress drop is of great importance.

The ratio of radiated energy to seismic moment, multiplied by the shear modulus yields the apparent stress. It should be noted that the seismic moment, seismic energy, corner frequency and apparent stress estimations are not model dependent. Figure 18 (top) shows static stress drop versus seismic moment for data from the Central Rand Basin area. Figure 18 (bottom) shows the relationship between $\Delta \sigma_{app}$ and $M_{0SH}$. There is a systematic increase in the stress drop with an increase in seismic moment. Despite a strong correlation, the data reveal a strong variation in the both stress drops ($\Delta \sigma_{app}$ and $\Delta \sigma_s$) for a fixed seismic moment.
Figure 18. Top graph shows relationship between static stress drop and seismic moment $M_{0SH}$ [Nm]. Bottom graph shows relationship between apparent stress drop and seismic moment $M_{0SH}$ [Nm].
7.1.3 Relationship between scalar seismic moments and corner frequencies

In this study, the focus was investigating the relationships between spectral parameters for the Central Rand Basin area. Relations between seismic moments and corner frequencies are one of the most important characteristics of seismic parameters for a studied area. Figure 19 shows seismic moment versus corner frequencies for the S-waves. Diagonal lines follow constant stress drops.

![Figure 19. The relationships between scalar seismic moment and corner frequency for data from the Central Rand Basin area. The lines of constant static stress drop $\Delta \sigma$ are shown as diagonal blue lines.](image)

Recently Hua et al., 2013 investigated the relationship between the impoundment of the Longtan reservoir and seismicity in the area and found
evidence that the seismicity was reservoir induced. The observed relationships between seismic moments and corner frequencies for several datasets are presented in Figure 20. Data from our study are marked with a translucent blue ellipsoid. Figure 20 is from the paper by Hua, et al., 2013. The ranges of seismic moments are similar varying from $10^{10}$ to $10^{14}$ Nm. However, the ranges of static stress drops are very different. The values of the static stress drop vary between 0.02 and 35 MPa for the Central Rand Basin area and between 0.001 and 0.7 MPa for the Longtan reservoir.

![Figure 20. Relationship between seismic moment and corner frequency. Graph from Hua et al., 2013 together with data from this study (transparent blue ellipsoid).](image)

Data from the Longtan reservoir have a much lower stress drop than the stress drop obtained for the Central Rand Basin. Induced earthquakes (not represented in this report) at the Koyna-Warna reservoirs in India also showed very low stress drops, < 2 MPa (Mandal et al., 1998). Several studies show that induced earthquakes appear to have systematically lower stress drops than tectonic earthquakes. However, there are some exceptions, i.e.
Tomic (et al., 2009) analysed a set of 101 $M_L \leq 2.1$ earthquakes induced by a changing water level in the Acu Reservoir, Brazil and estimated that their stress drops were in the range of 26–179 MPa. To explain those high values they argued that the earthquakes were intra-plate, reservoir-induced seismicity. The values of stress drops were closer to the fracture of fresh rock and the presence of water did not affect stress drop. It is widely accepted that intra-plate earthquakes have higher stress drops.

7.2 Spatial variation of seismicity in the Central Rand Basin Area

The evolution of seismicity in the Central Rand Basin for the period March 2010 to November 2012 is shown in Figure 21. Three snapshots are displayed: (top) seismicity before November 2011, (middle) seismicity during 2012 and (bottom) combined seismicity. The distribution of seismicity shows a significant reduction in the level of seismicity in the western part of the Central Rand Basin. Figure 22 is another plot of seismicity, where the size of the dots is proportional to $M_L$ magnitude. The strongest events during 2012 were observed in the eastern part the Central Rand Basin.
time window: 2010H03H25  2011H10H31

Johannsburg 10 km

time window: 2011H10H31  2012H10H31

26° 06' S

MHSC: –SIM 11-02-01
Figure 21. Epicenter locations for earthquakes in the Central Rand Basin.

The spatial distribution of the static stress drops obtained from the S-wave waveforms is shown in Figures 22. The earthquakes with the largest stress drops are observed in the eastern and central part of the Central Rand Basin. Most events have a static stress drop smaller than 5 MPa, however, events with high stress drops have to be included and considered in the prediction of strong ground motion.

\[ \Delta \sigma_S \ [\text{MPa}] \]

Figure 22. Distribution of seismic static stress drops for the events, where the size of the dots is proportional to the value of the static stress drop in linear scale.

The seismicity fluctuations in space are studied by dividing the Central Rand Basin into polygons of equal areas of 16 km\(^2\). Analyses include all polygons that contained at least one earthquake. On this basis, 67 polygons with the numbers of events varying from 10 to 115 (see Figure 23) were identified. The polygons are distributed equally across the Central Rand Basin area. During
the previous year there was no major increase in the number of polygons, but the number of events observed within each polygon increased significantly from between 5 – 55 to 10 – 115. An attention-grabbing feature is that the polygons located in the center and eastern parts of the studied area contain the most earthquakes.
Figure 23. (top) Area of the Central Rand Basin divided into polygons of equal area 4 km x 4 km. (bottom) Size and color of dots reflect the number of earthquakes per polygon.

7.3 Temporal variation of seismic parameters and seismic moment rates

A study of the temporal variation of seismic source parameters could lead to the estimation of future seismic activity in the Central Rand Basin area.
Figures 24 and 25 show the variation of some seismic source parameters with time. The time series of $M_L$ magnitude and static stress drop are displayed for the duration of the entire catalogue. Visual inspection reveals that the seismic system is not static. There are observed periods of highs and lows. To quantify characteristics of the time series, several distribution models were applied to fit the data. This was done using the normal distribution, Weibull distribution and Kernel distribution. The seismic source parameter displays a typical asymmetric shape. The outliers have significant contribution to the estimation of the seismic hazard and the future level of seismicity.

The Weibull distribution is commonly used in failure analysis and risk predictions for data sets with extremely small numbers of samples. The Weibull distribution is flexible and fits a wide range of data, including normally distributed data. The Kernel distribution is a non-parametric, density estimation. It fits a smoothed distribution based on a normal Kernel function and is evaluated at 100 equally spaced points that cover the range of the data. Kernel density estimation is a data smoothing problem (see for example Parzen, 1962). The Weibull and normal distributions do not agree convincingly with the smoothed Kernel distribution. Therefore, statistical methods that assume data should follow the normal or Weibull distributions should be applied with caution.
Figure 24. Time series of the $M_L$ magnitude.
The statistical procedure used to estimate the seismic moment rate is illustrated in Figures 26 (only $M_{0SV}$ component), showing cumulative seismic moment as a function of time. The blue lines were obtained using the least squares polynomial fit. The lines show the average release rate since 25 March 2010 for $M_{0SV}$ $2.3 \times 10^{13}$ Nm/year.

There are several features in the time distribution of earthquakes in the Central Rand Basin area that would seem to require some discussion. The most obvious is perhaps the concentration of large events (swarm) during the period from day 350 to 420 with the largest magnitude being 3.5. Interestingly, from the plot it can be seen that a major change in the cumulative seismic moment stared before the magnitude 3.5 occurred. A period of relative seismic quiescence is observed between day 220 to 350 and 700 to 900. A similar procedure is used to estimate the cumulative $M_{0SV}$, $M_{0SH}$, $M_{0P}$, $E_{0SV}$, $E_{0SH}$, and $E_{0P}$ rate (see the main report).

The relatively complete dataset of seismicity in the Central Rand Basin region is restricted to magnitudes greater than 1.0 or 1.5. It is obvious, therefore, that
the total moment release and slip rates calculated from such a dataset, without consideration of the contribution of smaller magnitudes, will be underestimated.
Figure 26. Cumulative seismic moments released in the Central Rand Basin area as a function of time (top) and time series of the $M_{0SV}$ seismic moment (bottom). Total seismic moment $M_{0SV}$ released is $\Sigma M_{0SV} = 3.8 \times 10^{14}$ Nm.

7.4 Strain Rate

Seismic moment rates have been estimated from seismicity recorded over 3 years. The distributed seismicity of the region is assumed to be caused by a number of faults at different stages of the loading process. Seismic moment can, therefore, also be related to the rate of local deformation in the Central Rand Basin area. The locations of the seismic events in the area do not fall along a single plane, but rather occur throughout a volume. Earthquakes
provide an indirect measure of the strain release within areas of distributed deformation (Kostrov, 1974). The strain rate was obtained using the average rate of seismic moment (see Table 2 in the main report) and the values are: $0.4 \times 10^{-9}$ year$^{-1}$ for the SV component, $0.5 \times 10^{-9}$ year$^{-1}$ for the SH component and $0.8 \times 10^{-9}$ year$^{-1}$ for P the component. We conclude that the predominant mode of seismic deformation (strain rate) in the Central Rand Basin is $0.57 \times 10^{-9}$ year$^{-1}$. The estimated strain rate could be used as one of the indicators of future seismic activity.

For comparison, typically intra-plate strain rates are less than $0.1 \times 10^{-9}$ year$^{-1}$ and are several orders of magnitude smaller than a typical plate boundary strain rate (Stein, 2007). For the localized weak zone model, lateral variation in the lithospheric strength concentrates stress and strain leading to local strain rates of up to $10 \times 10^{-9}$ year$^{-1}$. This is a few orders of magnitude larger than background intra-plate strain rates. Seismic strain rates for the entire Central and Eastern United States are estimated from historical seismicity and from several seismicity models. Typical strain rates are estimated to be in the order of $0.0001 \times 10^{-9}$ year$^{-1}$ to $0.001 \times 10^{-9}$ year$^{-1}$, except near historical earthquake zones, or some four to five orders of magnitude less than typical strain rates in California (Anderson, 1986). Anderson also identified pockets of high seismic strain rates of $10 \times 10^{-9}$ year$^{-1}$ in the New Madrid Seismic Zone and Middleton Place Summerville Seismic Zone near Charleston, South Carolina. These high values were directly attributable to a series of large earthquakes. The strain rate at selected locations in the Central Apennines, Italy, is $18 - 57 \times 10^{-9}$ year$^{-1}$ (Caporali, et al., 2003). Western Turkey has undergone dominantly N-S extension, and the dominant component of the strain rate is $10 \times 10^{-9}$ year$^{-1}$ (Eyiddan, 1988).

7.5 Conclusions

Three and a half years after pumping water was stopped in the ERPM mine, the evolution of seismicity has indicated that the Central Rand Basin area is not yet in
equilibrium. Because the Central Rand Basin seismicity is located directly beneath the densely populated area of Johannesburg, a full understanding of its mechanism is required. Seismic data clearly shows that the level of seismicity in the rock mass influenced by water ingress tends to be much larger than in the surrounding rock mass.

The number of earthquakes along the Central Rand Basin increased after water ingress into mining voids commenced. This fluid-induced seismicity is still observed. From the presented data it is clear that the level of seismicity in the rock mass affected by water ingress tends to be much larger than in the surrounding rock mass.

A catalogue of almost 1000 earthquakes was created and the spectral parameters of the events were estimated. A new relation between $M_L$ and $M_w$ was obtained. The relationship $M_W = 0.49 \ M_L + 0.85$ was estimated using values of $M_L$ from 0.2 to 3.5. Scalar seismic moment varied from $10^{10}$ to $10^{14}$ Nm. The range of SV-wave energy is from $10^3$ to $10^9$ J. The static stress drops calculated from S-waves vary between 0.02 to 35 MPa.

The relationships between stress drop and scalar seismic moment undoubtedly show that the stress drop increases with seismic moment. Nevertheless, the scattering of the static stress drop or apparent stress drop around a fixed seismic moment spans roughly 1.5–2.0 orders of magnitude.

Several comparisons were presented between the seismic source parameters obtained in this study and those of other regions. The dependence between seismic moment and radiated energy for different studies show a similar pattern. In the Central Rand Basin area the radiated energy of the seismic events increases with seismic moment while covering a range of seismic energies of about six orders of magnitude. There are also some significant differences. For example, Longtan reservoir in China produces seismicity with seismic moments in the same range as is observed in the Central Rand Basin area; however, the ranges of static stress drop for the two areas are different.
Spatial variation of seismicity in the Central Rand Basin area was analysed. The radiated seismic energy reveals that events with energies $10^7 – 10^8$ J were observed across the entire area of the Central Rand Basin. The distribution of seismicity shows a reduction in the level of seismicity in the western part of the Central Rand Basin during 2012. The strongest events recorded in 2012 were concentrated in the eastern part the Central Rand Basin area, around ERPM mine.

The earthquakes with the largest stress drops are observed in the eastern and central parts of the Central Rand Basin. The amplitudes of the ground motion are controlled by the static stress drop of a seismic event; therefore, the areas of large stress drop are also areas where strong ground motion is expected.

Seismicity fluctuations in space were studied by dividing the Central Rand Basin into polygons of equal areas of 16 km$^2$. The polygons are distributed equally across the Central Rand Basin area. In this past year of monitoring, no major increase in the number of polygons was observed, but the number of events per polygon increased significantly from between 5 – 55 to 10 – 115.

Earthquakes provide an indirect measure of the strain release within areas of distributed deformation. In the Central Rand Basin, the predominant mode of strain rate was estimated at $0.57 \times 10^{-9}$ year$^{-1}$. The cumulative seismic moment and cumulative radiated energy as a function of time were calculated. These time series indicate that the constant deformation rate model is not suitable for our data. However, the evolution with time of the cumulative parameters and estimated strain rate could be used as indicators of future seismic activity.

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