Chapter 2
Applications of Seismic Monitoring in Combating Rock Burst Hazard

Abstract This chapter describes the history of mine seismology. This history is not about hardware or software development but about interpretation and practical applications of the recorded seismicity analysis. It indicates that understanding and based on scientific principles analysis of recorded seismicity resulted in practical rock engineering concepts that in consequence improved safety and mining. This is what mine seismology is about. This took place in the age of analogue technology before the digital networks were invented. Practical outcomes of that pre-digital mine seismology are still valid and practiced at present. This establishes the intention of this book, which is to demonstrate that it is possible to make good use of the recorded seismicity. For this reason this book starts from the basis that is from what it takes to understand the input data for analysis and interpretation. It seems to me that at present the concept of understanding the input data is not considered as important.

Rock bursts and rock falls have posed a serious problem in gold mines of the Witwatersrand practically since the beginnings of the industry. Data on their incidence reveal that these events are the single most important cause of accidents and fatalities in gold mines. They also result in loss of production and of revenue. It is not surprising that these events have already for many years been, and continue to be, of great concern to the gold mining industry. Evidence of this is the fact that Government Committees were appointed in 1908, 1915, 1924 and 1964 to report on earth tremors and rock bursts. Despite the considered advice of those committees and continued efforts by the gold mining industry, the problem of rock bursts and rock falls remain as serious as ever, mainly as a result of the increasing extent and depths of mining. In the decade since 1964, there has been a growth in the science and practice of rock mechanics, for example: Hill and Dennkhaus (1961), Hodgson and Joughin (1967), Hodgson and Cook (1970), McGarr (1971), Steele and Ortlepp (1972), Salamon and Wiebols (1974), Spottiswoode and McGarr (1975), McGarr (1976a), Cook (1976), McGarr and Wiebols (1977) and Ortlepp (1978). However, by 1977 it was realized that most of the information which had been accumulated is dispersed throughout a great number of scientific and technical publications and in

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the proceedings of many conferences and some of the important practical issues concerning implementation have not been published or implemented in industry. For this reason it becomes necessary to bring together the scientific, technical and managerial knowledge regarding these problems. This has been done by the High—Level Committee on Rockbursts and Rockfalls, which was formed on the recommendation of the Research Advisory Committee of the Chamber of Mines of South Africa. This committee comprised of the Research Advisory Committee, the Technical Advisory Committee, the Association of Mine Managers and representatives of the rock mechanics engineers. This committee published in "An Industry Guide to the Amelioration of the Hazards of Rockburst and Rockfalls" (COMRO 1977). In this guide it was concluded, as far as seismic monitoring is concerned, that the use of seismic networks should result in:

1. Location of seismic sources
2. Indication of trends in ground behaviour
3. Planning and control of mining operations—providing the mechanics of rock bursts will become understood
4. Indicating areas which might be more active due to geological features or inherent stress

Today those objects are as valid as they were in the past.

2.1 Early Monitoring Facilities of South Africa

Before 1908 only a couple of tremors per year were known to occur in the vicinity of Johannesburg mines (Gane 1939). In 1911, a Wiechert seismograph was installed. This instrument recorded nearly 15,000 events, from 1911 to 1937. The first significant study of mine related tremors in South Africa started in 1939, when a surface array of mechanical recorders was installed. Those studies, despite their limitations, clearly showed the direct relationship between the face advance and seismicity (Gane et al. 1946). According to Finsen (1950), for the time period 1938–1949 over 29,000 mine tremors were recorded.

The first underground seismic system was installed in the late 1950s at ERPM (East Rand Propriety Mines) by Cook (1962). Using this system he was able to show, that most of the recorded events occurred in front of and close to the stope face. He was also able to classify the events roughly by size and based on this he concluded that only the largest of events resulted in rock burst damage. Joughin (1966) installed a nine seismometer network at Harmony Mine, Free State Gold Fields, from which he was able to show that not only did the seismic events locate in the reef plane and in the hanging wall, but that some events located along the dykes. He also observed that a small portion of events occurred a couple of hundred of meters above the reef in a sill. The importance of these first seismic observations was that they not only confirmed the close relationship between the mining and the seismic activity, but that the local geology played a major role in controlling the distribution of the events. They also indicated that mine seismology, even with limited knowledge, has a potential to provide management as to where an event would occur and the like hood of rock burst damage.

The next important seismological development was during 1970–1980 with the establishment of the Klerksdorp Regional Seismic Network in 1971 and its continuous upgrading, which started the wide-spread use of mine-wide networks for management information purposes. Studies from this network (van der Heever 1982) were directed at the relationships between the extensively faulted geology and the seismicity. The development by Brink (1978) of a single-station triaxial accelerometer unit for the location of micro seismic events opened a new era of mine seismology, viz. an attempt to predict larger events. Those developments established the potential for using seismic information for rock burst control management purposes. The majority of rock bursts in this area are associated with movement on major geological discontinuities. This type of mine induced seismicity for this region was recognized before 1981 and is described by several authors, for example van der Heever (1982) and Gay et al. (1984).

The Klerksdorp Regional Seismic Network was established in 1971 as a result of the abnormally high seismic activity observed during years 1960–1970. Some of those events resulted in rock bursts that caused several deaths and damage to underground excavations. Some damage to surface structures was also observed. The main objective of this network was to obtain some understanding of hazards associated with seismicity in the Klerksdorp area in order to introduce preventive measures. This network was a joint venture between the Chamber of Mines and the four mines of the Klerksdorp Goldfield; Vaal Reefs, Hartebeestfontein, Buffelsfontein and Stilfontein and it covered about 107 km^2. At the beginning (1971/1972), the network consisted only of five geophone stations. In 1973 the network was expanded to eight stations. During 1976/1977 another eight geophone stations were added. In 1982 the network consisted of 24 stations, and in 1988 it had already 29 stations, of which eight were surface ones, and the rest was located at depths up to 2700 m below surface. By end of 1988 I have investigated this network configuration for location accuracy (Glazer 1998). At that time the need for more accurate determination of location of the sources of mine tremors in general led to an increase in the number of stations in mine seismic networks. For this reason, optimization of the network configuration became a very important factor (Kijko 1977, 1978). This resulted in the development of methods and software which could test network configurations with respect to location errors. The area that was at that time covered by the Regional Network was large and amounted to over 300 km^2. For purposes of this study it was assumed that all stations are simultaneously operational, which in reality is never the case, the maximum velocity error is 250 m/s, the maximum error in the arrival time reading is 0004s and that the co-ordinates of the seismic stations are accurate. The analysis was made for an elevation of 2500 m below datum. The expected errors of foci locations were calculated in the XY plane and in the Z direction (depth). The analysis was done for two cases, firstly, when a seismic event triggers 5 stations, and then when it triggers 8 stations. This analysis indicated that most of the Vaal Reefs, Hartebeestfontein and Buffelsfontein areas had a maximum XYZ location error between 100 and 150 m, while the error in XY plane, indicated that most of the the Vaal Reefs, Hartebeestfontein and Buffelsfontein had good cover, with location error below 100 m. For the northern part of Vaal Reefs and southern part of Hartebeestfontein, this location error was below 50 m.

In order to verify the location accuracy and measure the seismic wave velocity five calibration blasts were made before 1982 in various areas, within the Klerksdorp Goldfield (van der Heever 1982). The result was that the network could reliably locate sources of seismic events with an accuracy corresponding to about 0.8 % of the seismic path lengths, providing corrections were made for waves travelling through the Ventersdorp lava and Transvaal dolomite. Those corrections were then calculated, and applied to surface stations.

The technical description of the network, as it was at the beginning of the 1980s is given by Scheepers (1982) and van der Heever 1982. From that time the network went through several upgrades and modifications. All the monitoring stations by this time were equipped with 14 Hz geophones which were installed as triaxal units in brass boats. In the case of underground stations the geophone probe was installed in a 5 m long hole drilled into the hanging wall. The analogue signal from the geophone was passed through amplifying and modulating circuits on the site, then through telephone cables along crosscuts, haulages and up the shaft to a transmitter located at the top of the headgear. This analogue signal was transmitted continually by V.H.F radio to the seismic office that at that time was located at Margaret Shaft on Stilfontein Gold Mine. The surface sites, located at remote locations were powered by solar panels. At the central processing office, the signals from 29 stations were collected, demodulated, filtered and then held in the processors memory buffers. All channels were then simultaneously monitored by a trigger circuit. The trigger was activated by simultaneous changes in at least five geophones. When a trigger impulse was given, a four second history of each channel was written into memory. The location of the event was then calculated from the first arrival times, which were read manually channel by channel. The event magnitude was then calculated from a duration scale, which was calibrated against magnitudes as reported by the Geological Survey, Department of Mineral and Energy Affairs, RSA (Webber 1988). The duration Klerksdorp Regional Seismic Network magnitude, M_{KRSN} itself, is given by the following relation:

$$M_{KRSN} = 1.45 \log D + 0.12$$

where D is the event duration in seconds.

It was common practice to correct magnitudes of those events that were also recorded by the South African Geological Survey Network to values as reported by them in their monthly Seismological Bulletins.

The source parameters of the events recorded by the Klerksdorp Regional Seismic Network were then estimated as follows:

The approximate moment was calculated using the formula (Hanks and Kanamori 1979):

$$\log M = 1.5\ M_{KRSN} + 9.1\ [\mathrm{Nm}]$$

The approximate seismic energy was calculated using the formula (Gutenberg and Richter 1956):

$$\log E = 1.5\ M_{KRSN} - 1.2\ [\mathrm{MJ}]$$

2.2 Application of Seismic Data in Rock Mechanics Practice

I have already proved that there indeed was mine induced seismicity monitoring taking place long time before the digital monitoring system was invented. Recorded data was then analysed interpreted and conclusions used for practical purposes. These applications are not only impressive but still valid and in use at present. This indicates that these who made them were researches of great calibre. This proves the case that one will always end with better results having a professional team and not up to date equipment in comparison to the case of second hand experts and the state of art hardware.

2.2.1 Applications Relating to 1970–1980

The original purpose of the Klerksdorp Regional Seismic Network was twofold:

1. Rapid and accurate event locations for prompt rescue and opening up operations.
2. Identification of seismically hazardous geological structures.

The aim was also twofold, to improve safety and productivity of the mines. With time the purposes of the seismic networks become more and more complex and included the following:

1. Identification of seismically hazardous mining situations in highly faulted ground
2. Establishment of criteria likely to result in seismically hazardous situations
3. Investigation of rock burst damage and its relation to focal mechanism of the event that caused it.

As early as 1973 a rock burst research project was formed by Anglo American Corporation in conjunction with the Mining Operations Laboratory of the Chamber of Mines of South Africa. The aim was to study all aspects of the rock burst and rock fall as encountered in deep-level South African gold mines and recommend approaches for the amelioration of the problem. During the first few years considerable progress was made in developing an understanding of rock burst and rock fall problems. In the next phase the project aim was concentrated on developing an understanding of the nature of the rock burst and the rock fall problem. The effects of energy release rate, geological discontinuities such as faults, dykes and joints and blasting were investigated. It then became apparent that a distinction should also be made between rock burst control measures and rock fall control measures as these constitute two essentially different problems. The findings of the Rockburst Research Project highlighted a basic difference between the nature of the rock burst and rock fall hazards (Lawrence 1977). It was found that the most suitable criterion for expressing the relative difficulty of mining on a particular reef or in a particular area is the spatial rate of energy release (ERR) due to mining. This single scalar quantity expresses the combined effort of the mining geometry, depth of mining, stoping width and some rock characteristics. The methods of calculation of the rate of energy release were described by Cook et al. (1966). It was found that the rock burst hazard is linearly related to energy release rate, whilst the overall rock fall hazard is apparently not so strongly related to the ERR and is more likely related to a combination of quality of support, stoping width, the mining method employed and the geological structure. From this it was concluded that control of rock bursts can therefore only be effected through a reduction of the average energy release rate, while rock falls, given a particular reef and mining method, can only be reduced by improving the quality of support. Those findings, even though only of a general nature, were valuable in making strategic decisions concerning the evaluation of mining lay-outs. The following conclusions were made at the time: In general, the so defined rock burst hazard is directly proportional to the energy released by mining. This implies that installed support of any kind does little to reduce rock burst frequency or energy and only serves to minimize the damage resulting from the rock burst.

In the linear relationship, rock burst hazard = k × ERR, the k value may vary widely from reef to reef, and from area to area on a particular reef. The k value can only be established from actual mining experience in the area or on the reef concerned. Once the value has been established this relationship should prove very useful in comparing alternative mining geometries for new mining areas. The overall rock fall hazard is not strongly related to energy release rate. In a given mining situation, the only practical way of reducing the rock fall hazard, short of changing the method of mining would be to improve the quality of support in the immediate vicinity of the working faces and gullies. By end of 1979 it was known that most mining induced seismic events are associated with geological discontinuities in the surrounding rock mass. These include dykes, faults, joints and bidding planes. The discontinuities represent planes of weakness and are therefore likely to fail first before mining induced stresses reach the high levels required for the fracturing of intact rock. Similar to the relations developed in global seismology that the maximum magnitude of an earthquake originating on faults is strongly related to the displacement on the fault, the following relationship for the Klerksdorp area was established (van der Heever 1978).

$$M = 0.32 + 1.88 \log D$$

where:
D is the fault throw in meters
M is the maximum Richter magnitude

From this relation it was concluded, that at least theoretically, the Kromdraai Fault with its 800 m displacement can become a source of a magnitude 5.6–5.8 event. In general, from this type of relation it could be concluded that very large rock burst are possible only where large displacement faulting exists. An important observation concerning the intersection of dykes and faults was made (Heunis 1977). It was found that these intersections act as point stress concentrations and generate small seismic events at a distance of few hundred meters away from an advancing face. For this reason it was concluded that this phenomenon manifesting itself strongly during the early stages of mining could be used to delineate dykes and faults before mining approaches them. This additional information could result in reduction of the rock burst and rock fall hazard when used for mine planning.

As far as geological discontinuities are concerned the following was concluded:

1. Large displacement faulting (40 m +) presents special rock burst and rock fall difficulties in that the risk of very large seismic events is considerably amplified by the presence of these faults. Little is known about methods of preventing the occurrence of these very large events.
2. In planning new longwall systems, the effects of known dykes and small faults in the proposed mining area can be fairly accurately estimated in terms of the rock burst and rock fall hazard as well as production. Allowance can also be made for the presence of dykes striking perpendicular to the direction of longwall advance.
3. In the case of slight faulting, it was estimated that the contribution of these geological discontinuities to the rock burst and rock fall hazard can be reduced by ensuring that long wall shapes are more or less maintained. In deep-level mines this additional effort would therefore appear worthwhile.

Advances in seismic recording systems have resulted in the development of highly efficient location techniques. These systems if introduced on new mines at a very early stage, preferably before actual mining commences, could prove extremely valuable as a strategic planning tool by revealing the presence of major geological discontinuities long before they are exposed by mining. At the same time a lot of effort was put into the study of the relationship between blasting and seismicity, for example (O'Connor 1978; Lawrence 1975). It was found that a significant number of recorded seismic events on a mine are associated with enlargement of excavations. If it is assumed that most of the mining induced seismicity is closely coupled to the actual enlargement of the stoping excavations, then continuous mining will distribute seismicity more uniformly in time, resulting in a likely increase of seismicity during shifts. Blasting in one area of a mine was found to increase rock burst probability elsewhere, depending on the distance and amount of blasting. This is of importance where adjacent mines blast at different times and would complicate the use of scattered blasting methods for reducing ore surge capacity requirements in deep level mines. The exact sequence of blasting between various sections using a centralized blasting system does not appear to significantly affect seismicity on later shifts. For instance, synchronized blasting is neither expected to aggravate nor alleviate the rock burst safety hazard of later shifts. The important factor is to minimize the exposure of people in stopes while blasting takes place in the vicinity. Optimum re-entry periods vary from reef to reef. Development of effective rock burst control strategies should on the one hand improve the safety at the underground working places in general, but on the other hand, should lead to limiting the occurrence and effects of single very large rock bursts. Reduction in the energy released by mining can be achieved by introducing partial extraction methods, by back filling or by reducing the stoping width in extensively mined areas. Design criteria and the advantages and disadvantages of various mining methods using partial extraction have been looked into with great of detail, for example in Cook et al. (1966), Salamon (1974), Wagner (1975, 1976) and Salamon and Wagner (1979). In deep-level mines with longwall mining the introduction of reef strike pillars spaced regularly along the entire length of the long walls proved, at the time, to be the most effective method of reducing the energy released by mining.

In the late 1970s and early 1980s it was hoped that the wide introduction of seismic networks into deep gold mining will result in the following:

1. Rock burst prediction, understood as identification of sites where rock bursts are going to take place in matters of hours so that evacuation of workers will be possible (Brink 1978)
2. Understanding of the interaction between induced and geological discontinuities and its relationship to the stability of the fracture zone surrounding the underground excavations
3. Development of seismic methods for delineating dykes and faults ahead of mining excavations for long term planning.
4. Understanding of the violent failure of large faults and dykes subjected to mining induced stresses.

2.2.2 Applications Relating to 1980–1990

Several years of recording and analysis of mining induced seismic events led to the quantification of the relationship between seismicity and parameters that control them. In general there are two types of such parameters, mining and geology. There are several mining parameters which influence seismicity, and those are, depth of mining, blasting, area mined and rate of extraction. It is assumed that seismicity increases with depth of mining. This relationship is difficult to quantify probably because of the influence of geological factors. Coal mining, which in South Africa is very shallow (100–300 m) does not generate any significant induced seismicity. The relatively shallow Rustenburg platinum mining region (800–1200 m) which is situated in an area which experiences a moderate level of natural seismicity has only several mine induced events in the ranges 2.0–3.0 magnitude annually. Evander and West Rand mining areas, which are deeper (1200–1600 m) are more seismically active, but events above magnitude 3.5 are not very frequent. The deeper mines (2200–2600 m) in the Orange Free State and Klerksdorp Goldfields experience irregularly spaced events that exceed local magnitude 4.5. The ultra—deep mines of the Far West Rand (below 2500 m), region generate relatively high levels of seismicity. The events are regularly spaced in time and their magnitudes are in the range between 2.5 and 3.8.

During the time period 1971–1990 the Klerksdorp Regional Seismic Network recorded about 15,000 events. All those events occurred within the mining boundaries. This is an indication that all those events are mine induced. According to van der Heever (1978) who investigated the relationship between blasting time and occurrence of seismic events, there is a substantial increase in the number of small events directly after blasting. Large events tend to be independent of blasting and take place at any time of the day. I have studied (Glazer 1997) the time distribution of seismic event occurrence in relation to the time distribution of released seismic energy. It was found that the distinctive peak in number of recorded events starts at 14h00 and ends at about 18h00 and that it is directly connected with the blasting time. This is illustrated by Fig. 2.1. The distribution of seismic energy released per hour does not correlate with the number of events per hour. This is illustrated by Fig. 2.2.

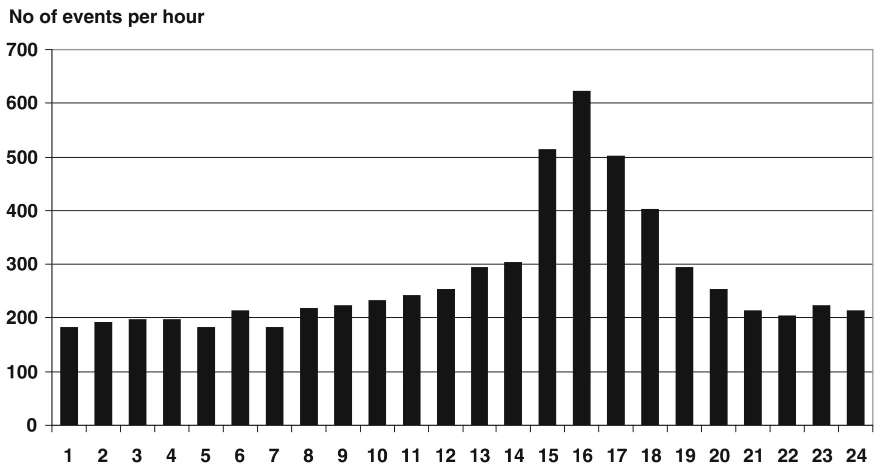

Fig. 2.1 Time distribution of recorded seismicity

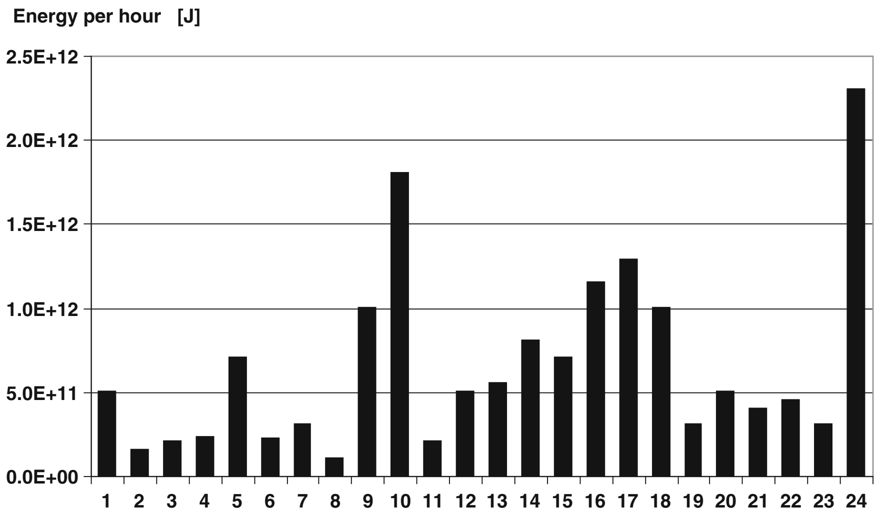

Fig. 2.2 Distribution or seismic energy release

While the peak number of events per hour correlates directly with the blasting time, the peak amount of energy released per hour comes 7 h later, between 22h00 and 23h00. There are in fact three distinct peaks in the energy distribution. The first one coincides with the peak of the number of events per hour, between 15h00–16h00, the second one between 20h00 and 21h00, which is twice as big as the first one, and the third and main one between 22h00 and 23h00 which is about 5.5 times as big as the first one. From the above analysis it was concluded that blasting on its own triggers a lot of events, but most of them are relatively small ones. While their number is high, a low amount of released energy is associated with them. It seems that there is some kind of ageing period of about 7 h, after which the high energy release events occur.

According to Gay et al. (1984), there is a good correlation between number of events and the total area mined (for data relating to 1971–1981). From the plot of cumulative energy released by seismic events against centares mined, a very interesting conclusion was made, that the occurrence of big events seems to be independent of mining activity. At that time, the relationship between rate of advance and seismicity was not defined, but it was regarded as good mining practice to keep it constant and not to advance beyond the normal stress induced fracture zone. As far as stoping width is concerned it was known that it influences mine seismicity due to the fact that the amount of seismically radiated energy is dependent on the elastic closure. The relation (McGarr 1976b)

$$Mo = G \cdot V$$

where:
Mo is seismic moment
V is volumetric closure (area x stoping width)
G is modulus of rigidity

states, that if a mined-out area would be subject to total closure, then doubling of the stoping width, would result in a two fold increase in seismically radiated energy. Regional support such as barrier pillars or backfill result in reduced elastic convergence and for this reason lower the amount of released seismic energy. Webber (1989) investigated the seismic deformation due to mining for the four mines of the Klerksdorp area. He used the following relationship,

$$\Sigma \text{Mo} = \gamma \cdot G \cdot \Delta V$$

where:
Σ Mo is cumulative seismic moment
G is modulus of rigidity
ΔV is volume change due to mining
γ is factor between 0 and 1

The value of γ was then evaluated for individual mines and for the whole district. It was found that the value of γ varied over individual shafts and production areas, but was relatively constant over the individual mines. It was then concluded that mine values of γ are dependent on the age of the mine and the ratio of the mined to un-mined area. More interesting findings resulted from the attempts to evaluate the γ values for individual production areas. In this case it was found that those values varied very much from area to area. The conclusion was that mining in one area influences the seismicity of another area.

Rock bursts in the Klerksdorp area have two main sources. The first is due to shear movement on faults, and the second are associated with highly stressed dykes, (van der Heever 1982). More than 10 years of recording seismic information allowed for the following observations in regard to faults:

1. Large events are usually associated with normal faults with throws between 10 and 200 m
2. Faults with throws of less than 10 m have events of lower magnitude
3. Fault planes with intruded dykes are more hazardous
4. Planar, regular and extensive faults planes are more hazardous than curved, splayed or composite ones
5. Dilatated fault planes with well defined contacts are more hazardous than multiple fault zones
6. Susceptibility to slip is unrelated to fault strike orientation
7. Events are biased towards the hanging wall of the reef in the up-throw block, and toward the footwall in the down-throw block.

The above observations, based on seismic monitoring, led to the development of strategies for mining near seismically active faults that can be summarized as:

1. Mine panels adjacent to the fault plane first
2. Keep adequate sidings and more intensive support near the fault
3. Gullies should be footwall lifted
4. Avoid excessive lags or leads
5. Final remnants must be remote from fault
6. Use pillars to clamp faults
7. Minimize fault exposures in service excavations

Dykes and sills have a significant influence on seismic event and rock burst distribution. Several studies have been done on the incidence of rock burst and seismic events for stopes which traversed dykes, e.g. Gay and Jager (1986) and Roberts and Brummer (1988). The results indicate that a substantial increase in the number of seismic events occurs when mining faces are within 30 m of a dyke. It was found that there are several factors that influence the seismicity levels on the dykes. The width of the dyke is an important parameter. Dykes which are up to about 5 m thick are too small to store large amounts of strain energy and usually do not become sources of large seismic events. On the other hand, very thick dykes, (above 60 m) are sufficiently large to render the strain energy in a stable pillar. It was found that the type of dyke is very important. Soft, weak and decomposed dykes are less seismically active than the strong, brittle fresh types. Well jointed blocky dykes are seismically less active than the intact massive ones. Again due to active seismic monitoring, the above observations allow for the development and implementation of the following mining strategies:

1. Avoid mining breast-on towards a dyke
2. Keep the number of dyke pillars to a minimum
3. Do not extract dykes with a lagging face configuration
4. Minimize the length of face which is within a dyke
5. Do not site vulnerable excavations in dykes
6. Leave reef pillars if stresses in the dyke exceed 60 % of UCS (uniaxial compressive strength)

Publications on the rock burst phenomena and methods of combating the rock burst hazard in deep gold mines in the 1980s are numerous, some of which are, Wagner (1984), Ortlepp (1983, 1984), Rorke (1985), Hepworth (1985), O'Ferrall (1986), Spottiswoode (1986), Roberts (1986), Gay (1986), Ryder (1986) and Gay et al. (1988). It is worth mentioning that this and other research work in regard to rock burst were used to complete "An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts." This guide was published by the Chamber of Mines in 1988 (COMRO 1988b) and was then implemented in all gold mines of South Africa.

The network in the Klerksdorp area that was started in 1971 was established in order to understand the hazards associated with seismicity in order to introduce some preventive measures. By early 1980 it was known that all large magnitude events in this area were related to geological features. Several hazardous faults and dykes were identified that were associated with large seismic events van der Heever (1984) and the influence of geology on the seismicity is described by Potgierter and Roering (1984). This resulted in the application of several support patterns and changes in mining sequences around those faults. Additionally, some protective actions for service excavations passing through those features were taken. A comprehensive summary of the strategies for combating rock burst hazard based on seismic information gathered in the Klerksdorp area is given for example by Gay et al. (1984) and O'Ferrall (1986). Seismic information was also used for planning and mining shaft pillars, for example Emmenis and O'Ferrall (1971), Taljaard (1992) or van der Heever and O'Connor (1994). The system was capable of informing management where the event took place in matter of minutes. This information was vital in the case of a large event and was used to start the rescue action, almost immediately in the area of concern. The number of recorded events increased in years due to the increase of the number of stations and varied from 40 to over a hundred per month. By 1989 it was accepted that the Klerksdorp Regional Seismic Network suffered the basic limitations of analogue transmission. All attempts to calibrate the system have been unsuccessful. However, studies of first motions recorded after big events resulted in reliable fault plane solutions. This gave information about the focal mechanisms of those events; van der Heever (1982), McGarr et al. (1989) and Rorke and Roering (1984). By the beginning of 1990, significant progress was made not only in development of hardware for seismic networks, but also in extracting source parameters from recorded seismograms. But the most important progress was made in the use of seismic source parameters for evaluation of underground hazard.

Starting in the 1970s, significant contributions to mine seismology studies have been made by the staff of the Bernard Price Institute of Geophysics, University of the Witwatersrand, Johannesburg. The results of research work of that time can be found in McGarr (1974, 1976a, 1981, 1984), McGarr et al. (1975, 1981, 1982), McGarr and Green (1975), McGarr and Wiebols (1977, 1978), Spottiswoode and McGarr (1975) and Spottiswoode (1980). Knowledge obtained from these seismic studies was then used for the design of rock burst support. This was done by Wagner (1984) when he used the ground velocity to analyze damage patterns of a number of seismic events. From this analysis Wagner was able to recommend improvements to support systems which were used at that time in stopes and tunnels. Studies of seismic data from the Carletonville area area have been concerned with both mine-wide data, for example Spottiswoode (1984, 1990), Hagan (1990) or, Lenhardt and Hagan (1990), and micro seismic data, for example Cichowicz and Green (1989), Cichowicz et al. (1987, 1988, 1990) or Green (1984). Contributions towards a better understanding of source mechanisms of mining induced seismic events also came from other parts of the world, for example, from Poland where a number of works have been published by the members of Institute of Geophysics, Polish Academy of Sciences, Warsaw. Examples of these are Teisseyre (1980), Gibowicz (1984, 1986, 1990a, b), Gibowicz et al. (1991). Other regions that made significant contributions is the Polish coal district, for example, Dubinski and Dworak (1989). All these and other contributions were then summarized in a book by Gibowicz and Kijko (1994) "An Introduction to Mine Seismology". The accumulated experience from several mine networks, Lawrence (1984), Brink and Mountford (1984), Waldeck (1988), Mendecki et al. (1990), Flannigan and Hewlett (1988), van der Heever (1989), Patric and Kelly (1988), COMRO (1988a), Hewlett and Flannigan (1989), Brink (1990), made it clear that the time of analogue technology in this application is over.

By the end of 1988 mine management was expecting from the seismic system the following (Glazer 1998):

1. Identification of seismically hazardous structures for strategic planning, sequencing and adequate support implementation
2. Recognition of seismically hazardous areas for implementation of adequate strategies to combat risk
3. Assessment of seismic source parameters for planning guidelines, for example for situating pillars along an active fault or for support design
5. 24 h management information service, for rescue and opening-up operations
6. Data base that can be used for planning purposes. For such a data base to be of use for rock engineering purposes it must contain not only accurate information in regard to locations of big events, but also of all small events lets say of magnitudes down to 0.5 (that was the requirement at the time, as far as sensitivity of a regional network is concerned). It must also contain as accurate as possible source parameters of those events, calculated from good quality seismograms.

The above requirements could not be fulfilled any more by an analogue seismic system. The Klerksdorp Regional Seismic network had to be upgraded to a digital system (Glazer 1997). In April 1989, the Klerksdorp Mine Managers Association (KMMA) gave its approval to implement the necessary upgrading. At that time, it was also agreed to reallocate the network itself, from its present remote location at Stilfontein GM, to a more central site at Vaal Reefs. The new location of the Klerksdorp Regional Seismic Network was chosen for two reasons. First for technical reasons, if the network was to expand, its number of stations had to increase. A centrally located site is best suited for radio communication purposes. The second reason, which from today's perspective, is much more important, because recent advances in communication systems have made the first reason redundant, was to situate the networks central site as close as possible to the Rock Mechanics Department, van Wyk and Coggan (1990). 2 years after the reallocation, the network and its staff became a section of the Vaal Reefs Rock Mechanics Department. This integration was a natural process, and indicated that seismic information became a more and more important part of the rock engineering recommendations. The new site was located close in the same building as the Vaal Reefs Rock Engineering main offices.

Figure 2.3 illustrates the fact that due to the continuous network enlargement after installation of the digital system by mid 1990 the number of recorded seismic events started to increase. This increase was obviously in number of small size events below magnitude 0.0. According to data presented by this figure the monthly

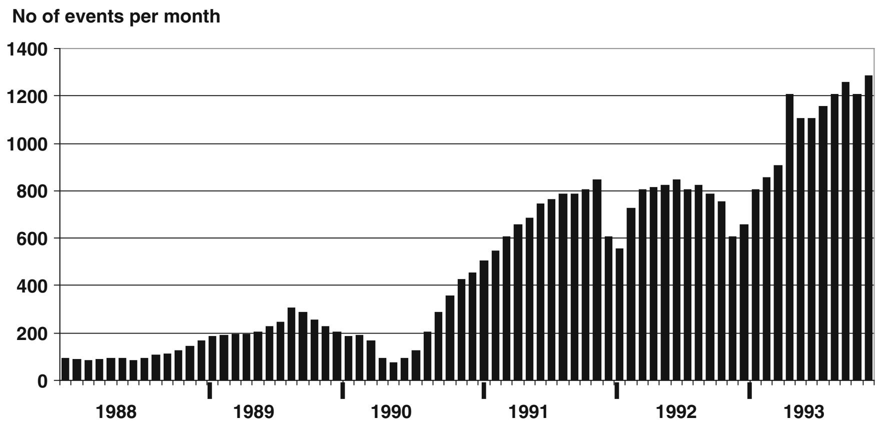

Fig. 2.3 Seismic activity rates between 1988 and 1993

activity rates increased from less than 200 events per month (1988) to nearly 1200 by mid 1993. In June 1997 there were 97 stations operational while another 33 were in different stages of installation. At that time the recorded number of events increased to about 30,000 events per month. This resulted in two problems that had to be addressed:

1. Capacity to process the recorded data
2. Data interpretation

The first problem was mainly manpower and at that time was solved quickly. As from June 1994 the seismic central site was manned 24 h a day, on a 3 shift basis. This resulted not only in improved quality of recorded seismic data, but more importantly, all events of damaging potential were immediately reported to the shafts. This allowed, when required, to send proto teams with no delay, or start the opening-up operations directly at the affected areas. The second problem was more complex as it required not only more of well qualified manpower but also development of new interpretation techniques that could cope with large amounts of seismic events (Glazer 1999).

2.3 Summary

Digital seismic recording systems started to operate in the mines during early 1990 years. Their main and undisputed contribution towards mine seismology was increased amount of recorded seismicity. Some researches claim that this recorded seismicity is of improved quality when compared to older data that was recorded with the analogue technology. In my opinion this is questionable. This becomes obvious when trying to list something new due to digital technology in the field of seismic data interpretation that wasn't done in the past. The success of seismic data interpretation should be measured in its contributions into rock engineering practical applications for combating rock bursts. Nothing really new in this matter happened during the last 25 years. All principles of mining in seismically active rock mass volumes are the same as 25 years ago and there are no new ones. It is accepted as true that the better understanding of the seismic source the more efficient anti rock burst measures can be applied. For this reason research into mechanics of the seismic source continues but with no practical results. Why is that so? The answer seems to be hard to believe as the issue is the digital technology itself. More precisely the problem is the general trust in the recorded data. It is considered not only of superior quality but deemed to be genuine in describing the seismic source. In my over 25 years practice in mine seismology I don't record any analysis of the input data and of what in reality are the seismicity parameters. This at present is considered to be of no importance. This indicates that at present the understanding of interpretation input data is generally not considered to be an important issue. It was definitely important before the digital seismic systems came to operate on the mines.

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