Chapter 2
Seismicity of the Klerksdorp Goldfields and the Resulting Seismic Hazard

Mining in this district started as early as 1886. Deep-level mining to 1500 m commenced in 1937/38. With increasing mining depths came the associated seismicity. The association of these seismic events with damage and injuries was such that, in 1969, it was decided to establish a permanent seismic network. This network was funded by all four mines operational at that time, in collaboration with the Chamber of Mines of South Africa. By 1982, it was established that all large magnitude seismic events in this region were related to geological features. Several hazardous faults and dykes were identified that were the source of seismic events. This resulted in the application of several changes in mining sequences and support patterns around those features. In addition, protective actions for excavations crossing geological discontinuities were implemented.

The Klerksdorp Goldfield lies on the north-western rim of the Witwatersrand basin (Fig. 2.1), about 160 km southwest of Johannesburg. The gold mines surround the towns of Klerksdorp, Stilfontein, and Orkney. The area, part of the so-called African Peneplane is about 1200–1500 m above sea level. The terrain is flat but has some hills (koppies) up to about 100 m high. The climate is typical for the Highveld. The summers are warm and sunny with about 600 mm of rainfall. The winters are sunny, dry, but cold with temperatures oscillating between −5° at night and up to +25 °C during the day. There are two rivers in the area, the Vaal River and the Schoonspruit.

Several conglomerate bands have been mined in the area. Starting with the oldest, there is the Dominion Reefs occurring in the strata underlying the Hospital Hill Series, then the Government Reef Series, the Commonage Reef (cover portion of the Main-Bird Series), the Vaal Reefs in the upper part of the Main-Bird Series, the Gold Estates Reefs of the Kimberley Series, the Ventersdorp Contact Reef (VCR) on top of the Elsburg Stage, and the Black Reef Series of the Transvaal System (Antrobus et al. 1986). Witwatersrand means "Ridge of White Waters". This is the name of the hills located north of Johannesburg. These hills form a watershed as the rivers of the southern slopes flow to the Atlantic Ocean, while the waters of those of the northern slopes end up in the Indian Ocean. The

S.N. Glazer, *Mine Seismology: Seismic Warning Concept*,
https://doi.org/10.1007/978-3-319-62353-5_2

Fig. 2.1 Localization of Klerksdorp

Witwatersrand basin is situated on the Highveld 1370–1829 m above sea level, some 550 km from the coast between longitudes 26° 30′ and 29° 15′E and latitudes 26° 00′ and 28° 15′S. The Witwatersrand basin is elongated in shape. It is about 150 km along a SE–NW direction and about 300 km along the NE–SW line. The centre of the Witwatersrand system is punctured by a structure known as the Vredefort Dome. Most of the conglomerates containing minable gold occur in the Upper Witwatersrand beds and most of the gold producing mines are situated along its outcrop close to towns such as Carletonville, Randfontein, Johannesburg, Springs, Heidelberg, Virginia, Welkom, and Klerksdorp. The first discoveries of gold were made on the Central Rand (Randfontein–Springs area). At present, this is the most populated and industrialised part of South Africa with Johannesburg located in its centre. The Witwatersrand System is closely related to the underlying Dominion Reef System and the overlying Ventersdorp System. Those three systems are often referred to as the Witwatersrand Triad. Below the, Triad are the granites, gneisses and schists of the Swaziland System. Those formations are of the early Precambrian age. Extensive major faulting has taken place along the strike of the beds, tangential to the basin. These faults occur for a large part in the beds of the Lower Witwatersrand, but in places they also affect the beds of the Upper Witwatersrand. These faults are the Rietfontein Fault (Central Rand), Witpoortjie and Roodepoort Faults (West Rand), Buffelsdoorn and Kromdraai Faults (Klerksdorp Goldfield), and De Bron Fault in the Orange Free State. Other major faults as the Sugarbush (East Rand) or the Bank Faults are transverse faults, orientated radially with respect to the Witwatersrand basin. These major faults are post-Ventersdorp and pre-Transvaal in age. Furthermore, the gold bearing reefs have been displaced by numerous relatively minor strike and transverse faults. The throw along any given fault plane may vary, which gives rise to a wedge of faulted ground along one side, of which the displacement can increase from zero to about 100 m. Many of the faults that cut the ore-bodies are occupied by dykes. Their age varies from Ventersdorp to Karoo and earlier (Whiteside et al. 1976). The Witwatersrand basin contains nine different goldfields. These are:

– Evander Goldfield
– South Rand Goldfield
– East Rand and Heidelberg Goldfield
– Central Rand Goldfield
– West Rand Goldfield
– West Wits Line
– Vredefort Goldfield
– Klerksdorp Goldfield
– Orange Free State Goldfield

2.1 History of Gold Mining in the Klerksdorp Area

The position of the sub-outcrop of the Vaal Reef has been determined by drillings, and the reef has been found to underlie an area of about 260 km^2 on the northern bank of the Vaal River. The Vaal Reef has also been intersected within a large area on the south side of the Vaal River, and the reef is mined in this sector of the field as well. Along the western margin of the Klerksdorp field, the truncation of the Vaal Reef has been affected either by the Buffelsdoorn Fault or by the unconformity associated with the Gold Estates Reef. Along the northern and eastern margin, the Vaal Reef sub-outcrops against lava or dolomite. Dykes and sills of various ages are common in the Klerksdorp goldmines. The oldest are related to faults, with varying amounts of throw, whereas the younger ones are not related to faulting. There are several intrusions that are pre-Upper Ventersdorp, several that are pre-Transvaal and several that are post-Transvaal.

It is not known exactly when the first Voortrekkers arrived in the Klerksdorp area, but in about 1837/1838 there were already twelve settlers on the west bank of the Schoonspruit (Bruns 1977). Klerksdorp derives its name from the first magistrate Jacob de Clerq. The year 1865 saw the first trading business to be opened—The Taylor and Leask General Dealers. After the discovery of diamonds in the Kimberley area, the volume of trade increased. The first inn “Hail Smilin Morn” became popular with those travelling to and from the diamond area. In 1886, when gold was discovered on the Witwatersrand, Klerksdorp became a popular stop-over point between Kimberly and the Witwatersrand. The fortunes won on the Reef encouraged local prospecting in the Klerksdorp area. The first recorded successful prospecting was done by Apie Roos, a grandson of one of the first Voortrekker settlers. In the Pretoria archives, there is a letter dated 23rd August 1886 from Mr. Roos addressed to the President of the Zuid-Afrikaansche Republiek, Mr. Kruger. In this letter, he states that he had discovered a gold-bearing conglomerate, a sample of which was assayed at 27 penny weights per ton (42 g per ton?). As it stands today, the exact spot of this first discovery is unknown. According to official records, the starting date of the Klerksdorp Goldfields is 11th July 1887, when the farm Rietkuil was proclaimed. In a very short time, hundreds of fortune seekers with small blocks of claims started the formation of companies and syndicates. Mines were opened up, flourished for a while, then closed down again only to be re-opened by another company under a new and better sounding name. The Klerksdorp village got its first permanent brick buildings, houses, shops, hotels, churches, stores and offices. At one stage, it had no less than 68 licensed bars, liquor stores and wholesale liquor shops. One can imagine that these must have been the scene of many drunken parties and fights (Brown 1983).

On the Black Reef Series ridge, known as the Bosrand and running northwards from Orkney between Klerksdorp and Stilfontein, more than 20 mines operated at various times. The most important were Machavie, Eastleigh, Ariston, and Orkney. Colourful company names, such as Comstock, Banket Sheba, Nancy Lee, Royal Windsor, Shamrock, Ada May, Rose Beryl, and Beatrice were created to attract money from unsuspecting overseas investors. A few companies lasted longer than others, but only a few of these mushroom firms survived for more than a few years. Yet despite the fact that most of the individual mines were small, a stock exchange, rivalling that of Johannesburg was opened in 1888. It was then closed about a year later. Still, it saw some brisk business and it is recorded that, during one particular day, the transactions amounted to £10,000. After its short life, the exchange site became the centre of the town’s amusement and for 40 years was used for dances. Although the village of Klerksdorp was surrounded by mining activity during this period, it must be remembered that, for the most part, those were individual efforts on a very small scale. The shafts were all inclined, the headgears were of small wooden construction, and the crushing was done by three- or five-stamp batteries. The geological information was very scanty and the metallurgical processes had very poor recovery rates. On top of this, capital was always a major problem. Despite those difficulties, gold production continued to increase. The real boom lasted from 1894 to the outbreak of the Anglo-Boer War. In 1895, a peak output of over 70,000 ounces (1984 kg) was reached. This record production was reached again only 40 years later. From 1900 to 1902, all production came to a standstill. Many of the headgears were broken down and then used as firewood by British or Boer forces, who alternately occupied Klerksdorp on numerous occasions. After the signing of the peace treaty, the local mining industry made a slow recovery. By 1911, gold production had reached 30,000 ounces (850 kg) a year. This figure was maintained until 1915, when the effects of the First World War were felt. The almost complete cessation of mining activities during the First World War was a very serious blow to the local industry. It then recovered from this recession only in

1934. During this period, the Afrikander mine was often the only producer in the entire district. In 1933, Dr. Louis T. Nel of the Geological Survey of South Africa began his investigations in the Klerksdorp area. He published his finding in 1935, in which he presented the first proper map of the Klerksdorp–Ventersdorp area (Nell 1935). As a result of this new information, interest in the area was rekindled, and the large mining houses took a strong interest in the area. Anglo Transvaal opened the New Klerksdorp Gold Estates; New Union took over New Mines and the old Klerksdorp Proprietary mine; and New Machavie was then reopened jointly by Anglo-French and Barbrosco. The Afrikander and Dominium Reef were restarted by Bewick and Moering. Several smaller mines were opened up as one-man shows. The biggest commitment came from Anglo American. As a result of South Africa going off the gold standard in 1933, the Anglo American Corporation realised the importance of extending their gold-mining operations. As a result, all possible further areas for prospecting were investigated. After extensive searching, boreholes intersected payable values in the Ventersdorp Contract and Elsbury Reefs. This led to the first large mine, Western Reefs, which came into production in 1941. Disregarding the small workings, there were at that time only seven mines in the district, but such was the magnitude of their operations that the old production record of 70,000 ounces a year was soon surpassed. Initially, this was due to the high output from Machavie, but later Dominion Reefs and Western Reef played an increasing role. It seemed as if, at last, the area's promise was to be realised when, in 1939, the Second World War broke out. Although this was not to be as crippling as the First World War, it still caused a severe setback due to the curtailment of prospecting operations and an increase in the working cost. New Machavie closed down in 1944. During the closing stages of the war, drillings in the Orange Free State, south of Klerksdorp, revealed highly payable values of gold, and the attention of the financiers moved south. Still, Anglo-Transvaal invested in the Klerksdorp area by having New Klerksdorp Gold Estates take over the struggling New Mines. Anglo American continued their exploration of the area east of Western Reefs. At the same time, a company named New Pioneer began drilling on the farm Stilfontein and, in 1948, hit the jackpot. Klerksdorp's new era had begun. Three mines were opened: Stilfontein, Hartebeestfontein, and Buffelsfontein as a joint operation between Anglo-Transvaal and New Pioneer. Anglo American Corporation also opened a new mine Vaal Reefs east of Western Reefs. Jointly with Anglo-Transvaal, Zandpan Gold Mining Company was formed and Scott's Company established a mine called Ellaton. Barbrosco and Dominion Reefs had been forced to close down due to lack of pay ability and rising costs (Guest 1938, 1987).

Because of the encouraging borehole results from the Vaal Reefs horizon being drilled to the east of Western Reefs, the Vaal Reefs Exploration and Mining Company acquired nearly 7000 claims. The transfer of property took place in January 1946. During the following years, several shafts were sunk, such as No. 3 Shaft between 1949 and 1951, No. 4 Shaft between 1960 and 1961, and No. 2 Shaft in 1959. In August 1966, Vaal Reefs announced that it had plans to explore the Vaal Reefs horizon in the area south of the Vaal River. This new area

Table 2.1 1996 production figures

Mine	Gold (kg)	Tons milled × 1000	Grade g/t
Vaal Reefs	67,326	13,393	8.55
Hartebeestfontein	10,543	1500	7.03
Buffelsfontein	7600	1000	13.00

was to be worked as an extension to the mine's existing lease area and was to be known as Vaal Reefs South. The Vaal Reefs complex was formed on 20 September 1971, with the merger of three mines: Western Reefs, Vaal Reefs, and Vaal Reefs South. Up to 1998, Vaal Reefs Exploration and Mining Company operated several shafts at different stages of their productive lives, from very mature, with very limited time left, to those that were still in the early production stage or only at the sinking stage. Apart from Vaal Reefs Exploration and Mining Company, the Klerksdorp Goldfield during 1997 had two more operational mines, Hartebeestfontein and Buffelsfontein. The Stilfontein Gold Mine closed down its operations in 1992. The 1996 gold-production figures are presented in Table 2.1.

2.2 Seismicity of South Africa

Southern Africa is regarded as one of the most stable regions of the Earth as far as seismic activity is concerned. This region shows typical inter-plate seismicity with only a sporadic occurrence of natural earthquakes. Due to the relatively short documented history, little is known of the seismic history of the region. The Earthquake Catalogue of the Geological Survey of South Africa lists seismic events based on observations of its South African Seismograph Station Network since 1971. This catalogue shows that two types of seismic events occur: natural earthquakes and mine tremors that are associated with local mining activity. Southern Africa is located in the interior of the large African Plate. The borders of this plate in the south are the mid-Atlantic and mid-Indian Ocean ridges. The line of shallow seismic foci along these borders is continuous and well-defined. The continent itself is not affected by the distant tremors of this belt. The East African Rift System, another clear line of seismicity, has not been unequivocally shown to extend into Southern Africa, although the relatively higher seismicity of Mozambique, Zimbabwe, and northern Botswana can perhaps be considered as due to a southern extension of the Rift System.

The seismicity of the interior of the African Plate, especially in its southern portion, is, by world standards, very moderate and of a shallow character. In the rest of Southern Africa, two areas have been affected by large earthquakes. One is the southern Orange Free State, affected in 1912 by a shock of maximum intensity IX on the Rossi-Forel scale, and the other the Ceres-Tulbagh region of the Cape Province, where an earthquake of magnitude 6.3 on the Richter scale occurred in 1969. Occasional bursts of seismic activity have occurred at numerous other places in South Africa. As the catalogue indicates, the occurrence of earthquake swarms is not infrequent. This is the case for the series of tremors at Sutherland in 1952 and on the Cape-Lesotho border in 1953. The eastern coast of Southern Africa has been affected by tremors with epicentres in the Mozambique Channel (Fernandez and Guzman 1979a). In view of this pattern of seismicity it is difficult to correlate earthquake foci with geological features. Earthquakes have occurred on the ancient cratons, as well as in the mobile belts. The Cape Fold Mountains and the adjacent Karoo basin are equally subject to sporadic activity. Even tectonic features suspected on geological grounds to be active, such as the Doringberg Lineament, do not appear, in the long term, to be correlated with more tremors than are other features. The historical record of seismicity in Southern Africa is not only restricted in time, but is also affected by the uneven distribution of human population. As more instrumental records are obtained, the human factor will be eliminated, and the genuine areas of seismic activity will be revealed. According to Fernandez and Guzman (1979b), the number of natural earthquakes in Africa from the beginning of the 20th century to the end of 1970 is as follows (Table 2.2).

In the catalogue of natural earthquakes of Southern Africa, which starts from 1620 and ends in 1970 (Fernandez and Guzman 1979a), there are listed only three events that are located close to Klerksdorp (±80 km); see Table 2.3. The tectonic events and the mine-induced tremors form two different sets of data and for this reason should be studied independently (Shapira et al. 1989).

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, which 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

Table 2.2 Number of earthquakes in South Africa (1900–1970)

Decade	No of earthquakes
1900–1910	34
1910–1920	59
1920–1930	47
1930–1040	32
1940–1950	22
1950–1960	53
1960–1970	52

Table 2.3 Earthquakes close to Klerksdorp

Date	Richter magnitude
1935/09/11	Between 3.0 and 4.0
1952/06/29	M = 3.2
1970/08/30	M = 3.7

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 were the seismic events located in the reef plane and in the hanging wall, but that some events were located along the dykes. He also observed that a small portion of the events occurred a couple of hundred of metres 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 used with limited knowledge, has a potential to provide management the likely location where an event would occur and the likelihood of rock-burst damage.

The most important seismological development during 1970–1980 was the establishment of the Klerksdorp Regional Seismic Network in 1971 and its gradual upgrading, which started the widespread use of mine-wide networks for management information purposes. Studies using this network (van der Heever 1982) were directed at the relationships between the extensively faulted geology and the seismicity. Those developments established the potential for using seismic information for rock-burst control management.

2.3 The Klerksdorp Regional Seismic Network

Rock bursts and rock falls have posed a serious problem in gold mines of the Witwatersrand practically since the beginning 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 remained 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. However, by 1977, it was realised that most of the information that had been accumulated is dispersed throughout a great number of scientific and technical publications and in 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 was 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 the Research Advisory Committee, the Technical Advisory Committee, the Association of Mine Managers, and representatives of the rock mechanics engineers. This committee (COMRO 1977) published “An Industry Guide to the Amelioration of the Hazards of Rockburst and Rockfalls”. In this guide, it was concluded, as far as seismic monitoring is concerned, that the use of seismic networks should result in:

– location of seismic sources
– indication of trends in ground behaviour
– planning and control of mining operations—providing the mechanics of rock bursts will become understood
– indicating areas that might be more active due to geological features or inherent stress

All those objects are valid today.

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 of the Chamber of Mines and the four mines of the Klerksdorp Goldfield: Vaal Reefs, Hartebeestfontein, Buffelsfontein, and Stilfontein. At the beginning (1971/1972), the network consisted of only 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 reached 29 stations, of which eight were surface ones and the rest was located at depths up to 2700 m. The distribution of those stations among the mines was as follows:

Vaal Reefs	13 stations
Hartebeestfontein	8 stations
Buffelsfontein	6 stations
Stilfontein	2 stations

Figure 2.2 illustrates the network configuration as it was in July 1988. 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. As far as velocities are concerned, the following values were established (Table 2.4).

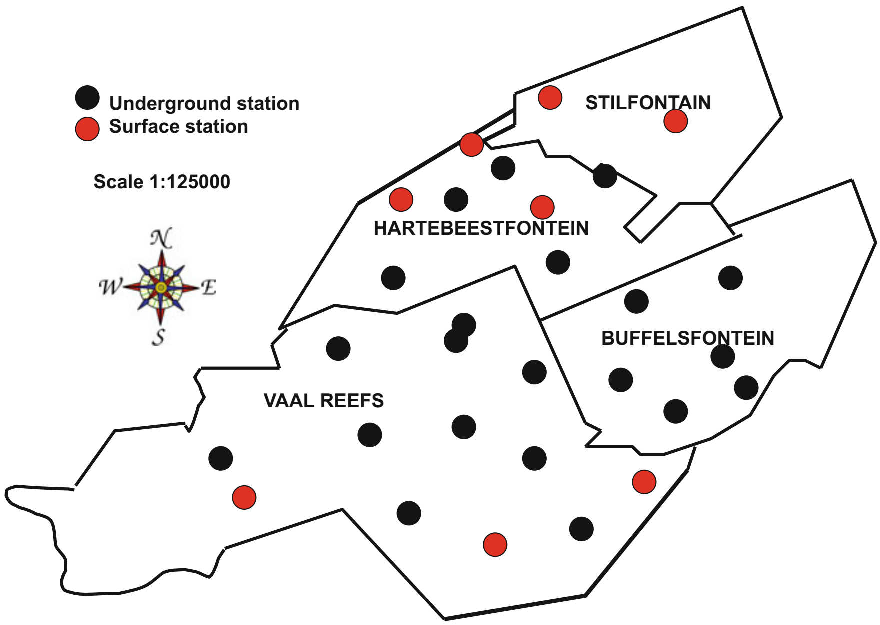

Fig. 2.2 Klerksdorp Regional Seismic Network, 1988

Table 2.4 Seismic wave velocities for Klerksdorp area

Rock type	Vp (m/s)	Vs (m/s)
Witwatersrand quartzite	5675	3575
Ventersdorp lava	6360	4150
Transvaal dolomite	6260	Not determined

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 triaxial 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 VHF radio to the seismic office that at that time was located at Margaret Shaft in the 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 on a duration scale, which was calibrated against magnitudes as reported by the Geological Survey, Department of Mineral and Energy Affairs, RSA (Webber 1988). The Klerksdorp Regional Seismic Network duration magnitude, M_{KRSN} itself, is given by the following relation:

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

where D event duration in seconds.

It was common practice at that time 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 seismic 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 an Richter 1956):

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

2.4 Severity of the Klerksdorp Goldfields Seismic Hazard

It is difficult to find information about mine-induced events for the time before 1971. However, some information could be found in local newspapers. The Western Transvaal Record (23/02/68), for example, reported that mine fatalities were once again put under the spotlight, when it was revealed that, during 1967, no less than 101 workers were killed in the six gold mines operating at that time in the region. Of this number, 60% of the fatalities were caused by falls of ground. This type of news about mine-related fatalities dominated the local news media throughout 1968. In July 1968 the fatality figure stood at 60 workers killed for the year. As the South African Seismograph Station Network started to operate only in 1971, the recorded number of events for the Klerksdorp Gold Mines during 1971 and 1972 can be an indication of the seismic hazard experienced in this area before 1970. For 1971, this network recorded 23 events of local magnitude above 3.0 and, for 1972, 19 events of such magnitude. The biggest rock-burst-related accidents were also reported by the local press. What follows are two such reports relating to rock-burst related accidents, one at Vaal Reefs and the other at Buffelsfontein. Vaal Reefs experienced some troubled times (Western Transvaal Record 07/03/74), when a rock burst trapped some 18 miners underground, of which only nine survived. In spite of every effort made by rescue teams from the mine, as well as surrounding mines, the remaining workers could not be reached in time. In March, the mine announced that the rescue operations were to be abandoned and the area sealed off. Eight bodies were to be entombed for ever. On Wednesday, April 26, 1978 at 11:00, Buffelsfontein mine experienced one of its worst rock bursts in history, which registered 4.6 on the Richter scale (Western Transvaal Record 28/04/1978). It was to be one of the strangest incidents in mining accidents that ever happened in the Klerksdorp Goldfields. An earlier tremor in the day caused some extensive damage to a stope on the 27th level of the Southern Shaft of the mine. No injuries or loss of life were reported during this tremor. Some mine officials proceeded underground to investigate the damage that occurred in this 27-level stope. As if fate had summoned them underground, another more severe rock burst occurred soon after these officials reached the damage area, and five men were killed. Rescue operations were immediately instituted, and the papers even published extra pages in the Friday edition of the Klerksdorp Record in order to report on the accident at the mine. What makes this accident that more important to the mining industry is the fact that the damage to the haulage where the men were killed could not to be opened in the weeks to come and it was truly a sad day in the history of Buffelsfontein GM as yet more people were to be entombed in a mine.

One of the largest events in the history of the Klerksdorp Goldfields took place on 7 April 1977 at Vaal Reefs. This tremor was recorded by 40 seismological stations around the world, and the US Geological Survey assigned a body-wave magnitude (m_b) of 5.5 to it (Fernandez and van der Heever 1984). The local Richter magnitude was determined by the South African Geological Survey to be 5.2. The main tremor was followed by an aftershock swarm. (Fernandez and Labuschagne 1979). All access tunnels close to the focal region were rendered inaccessible, while scattered falls occurred over an area of approximately 7.0 km^2. The main shock also resulted in appreciable damage to structures in the surrounding towns of Klerksdorp, Orkney, and Stilfontein. 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). A second event of similar size took place about 26 years later. A seismic event with a local magnitude of $M_L = 5.3$ occurred at 12:15 on 9 March 2005 at DRDGOLD's NorthWest Operations in the Klerksdorp district. The event and aftershocks shook the nearby town of Stilfontein, causing serious damage to several buildings and causing minor injuries to 58 people. At the mine, two mineworkers lost their lives, 20 mineworkers were injured at various locations in the No. 5 Shaft underground workings, 40 mineworkers were trapped in the stope for about 8 h, and 3200 mineworkers were evacuated under difficult circumstances. The third such large event took place on 05 August 2014 and was of local magnitude $M_L = 5.5$. The earthquake was felt in South Africa as far as away as Cape Town. It was also felt in Maputo, Mozambique, and in Botswana (Midzi et al. 2015). Surface damage was reported in Orkney where 500 houses were destroyed. Many people were injured, and one person was reported to have died as a result of a wall collapsing on him. Mining Company AngloGold Ashanti reported that 17 employees at two mines in the Orkney region sustained minor injures. The events on 9 March 2005 raised some wider questions. Are the technologies available to manage seismicity adequate in the current situation of remnant mining, deeper mines, and mining within large mined-out areas? Are current approaches to planning, design, monitoring, and management appropriate and adequate? Does mining, past and present, trigger or induce large seismic events and will it continue to do so in the future? Can the impact of seismicity on mining towns and communities be limited, and, if so, how? (Durrhein et al. 2006). The investigation after this event resulted in classifying this event and similar-in-type events as triggered by mining operations. Still, it remains surprising that for many mining specialists this event was such an unexpected occurrence. According to an assessment of seismic hazard in the Klerksdorp area (Gibowicz and Kijko 1994), the maximum expected event magnitude is well above $M_L = 5.0$ with a recurrence time of more than 20 years. This information is public knowledge as it was published and should be something that one would expect mining experts to know. In my Ph.D. thesis (Glazer 1998), I have written that seismicity of magnitude sizes from 3.5 and up is triggered not by present mining operations but by the entirety of mining that took place in the area from the start of mining operations. An example of such an event was one recorded on 10 February 1997. This was an event of magnitude 4.3 (see Sects. 3.3.1 and 4.11). Table 2.5 lists the number of events recorded by the Klerksdorp Regional Seismic Network from January 1972 to September 1990.

Note the increase in the network's sensitivity in 1977, when it started to record events of M_{KSRN} below 1.0. The next increase in the number of recorded events of M_{KSRN} below 1.0 was in 1989. These are the events recorded by the Chamber of Mines micro-network at No. 5 Shaft, Vaal Reefs. The number of recorded events of this size dropped again in 1990 due to the upgrading of the network which took over six months.

The original purpose of the 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 became 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 relationship to focal mechanism of the event that caused it.

Application of seismic research that was based on seismicity recorded by the KMMA Regional Seismic Network into rock engineering and mining during the time period from 1970 up to 1990 are described in great detail by Glazer

Table 2.5 Number of events recorded by the Klerksdorp Regional Seismic Network

Year	Below 1.0	1.0–1.9	2.0–2.9	3.0–3.9	Above 4.0	Total
1972	0	37	185	21	2	245
1973	0	86	96	22	2	202
1974	0	151	88	21	2	262
1975	0	47	36	16	1	100
1976	2	32	59	18	3	114
1977	163	231	114	21	4	515
1978	237	587	305	79	2	1210
1979	182	425	235	49	4	895
1980	111	275	202	42	4	634
1981	101	324	172	32	1	630
1982	190	380	157	34	5	766
1983	386	594	172	50	15	1217
1984	397	370	158	50	9	984
1985	156	433	161	37	5	792
1986	159	418	215	28	2	822
1987	394	264	176	32	2	868
1988	324	421	258	39	4	1046
1989	1087	947	351	57	2	2444
1990	193	1066	432	87	2	1780
Total	4082	7070	3572	735	71	15,530

(1998, 2016). These applications are still practical and applicable to mining in areas that experience induced seismicity.

A statistical assessment of seismic hazard in the Klerksdorp area is given in Gibowicz and Kijko (1994). This is an example of the application of a technique used in the case of an incomplete and uncertain catalogue of seismic events (Kijko and Sellevoll 1989, 1992) for data recorded by a mine seismic network. This method is a maximum-likelihood method for estimating hazard parameters, such as maximum regional magnitude M_{max}, seismic activity rate λ, and the b parameter of the Gutenberg-Richter relation. The catalogue of seismic events that was used at that time for the calculations was prepared at the end of 1991 and included events as recorded by the Klerksdorp Regional Seismic Network from 1 January 1972 to 31 December 1991. Due to the known history of seismic monitoring in the area, this catalogue was divided into three parts. The first part covers the time period from 1 January 1972 to 31 December 1984; the second part is for the period 1 January 1985 to 31 December 1990; and the third part is for the period 1 September 1990 to 31 December 1991. This catalogue was divided into three parts because of the monitoring facilities existing at that time. In the beginning, the network had only a few stations in operation. A larger number of stations were in operation only from the beginning of 1985 (±20 stations). In September 1990, the upgrade from analogue to digital was fully implemented. The drop in the number of recorded events at the beginning of 1990 was due to switching between the systems. After this drop,

Table 2.6 Threshold magnitudes and standard deviation values

Catalogue part	M_{min}	Standard deviation
Part one	3.0	0.3
Part two	2.7	0.2
Part three	2.5	0.1

there is a clearly visible steady increase in the number of recorded events right to the end of 1991. For the above reason, the following criteria were introduced (Table 2.6).

In total, this catalogue included 1559 events, which were split equally between the three parts (514, 522 and 523 events). As all the events before 1990 were, as a matter of routine, converted to values as given by the Geological Survey Bulletins, only those recorded after September 1990 had to be recalculated. It was assumed that the maximum, observed local magnitude was equal to 5.0. With the above assumptions, the following values were calculated:

$$\beta = 2.90 \pm 0.07$$
$$\lambda = 692.8 \pm 35.1 \text{ per year. (for } M_{min} = 2.0)$$
$$M_{max} = 5.19 \pm 0.15$$

From the mean return graph, the following could be concluded (Table 2.7).

It is interesting to note that the largest seismic events in the Klerksdorp Goldfield took place on 7 April 1977 (event size 5.2) and then, after nearly 25 years, on 9 March 2005 (event size of 5.3). The extent of the hazard resulting from seismic events is illustrated by Table 2.8, which shows the number of potentially damaging events in the Klerksdorp area from 1989 to end of 1996, together with the number of fatalities due to seismic events, for the same period.

Table 2.7 Magnitudes and their mean return time for Klerksdorp Gold Fields

Magnitude	Mean return time
Above 5.0	22.5 years
Above 4.0	6 months
Above 3.0	10 days

Table 2.8 Klerksdorp Goldfields, seismic event statistics for 1989–1996

Magnitude	1989	1990	1991	1992	1993	1994	1995	1996
Above 4.0	2	2	3	0	5	1	2	1
3.0–4.0	57	87	121	118	102	84	70	69
2.0–3.0	351	432	814	793	625	641	554	443
Fatalities due to seismic events	6	28	11	12	18	10	5	16

Table 2.9 Lost time injuries due to seismic events at Vaal Reefs

Year	1989	1990	1991	1992	1993	1994	1995	1996
Lost time injuries	66	61	121	41	60	106	32	85

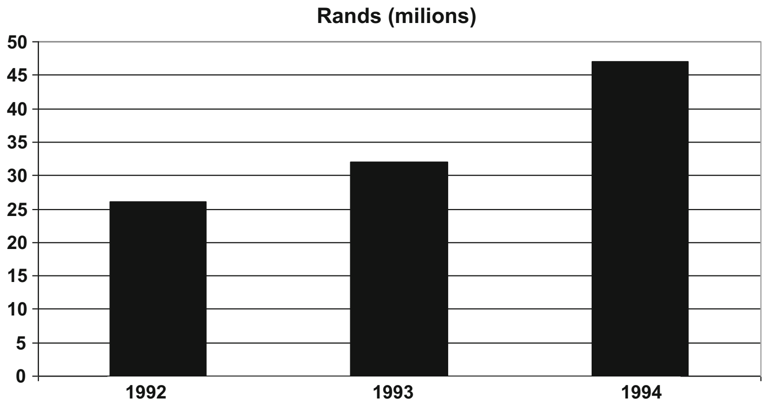

Fig. 2.3 Total cost of lost production for Vaal Reefs

It is easy to count the number of lost lives but a bit more difficult to establish the lost time due to injuries. Table 2.9 shows the lost-time injuries for Vaal Reefs for the time period 1989 to the end of 1996.

It is extremely difficult to establish the total cost of lost production due to seismic events. Figure 2.3 gives a very rough estimate of such costs. This estimate takes into account only the lost production costs including stoping and development costs due to seismic related damage. It doesn't take into account the costs of lost equipment or the cost of reopening operations.

Figure 2.4 illustrates the yearly seismic energy release rates from 1972 up to 1990, based on data recorded by the KMMA Regional Seismic Network recorded from 1972 through 1990. The average yearly seismic energy for this time period is 2.68E + 11 J. In comparison, the total seismic energy released at Palabora Mining Company for the time period 2001–2013 was 3.38E + 08 J. The 13-year seismic energy release at Palabora is nearly 800 times less from the annual seismic release at Klerksdorp (Glazer 2016). In other words, one year of Klerksdorp seismic-energy release is equal to an underground explosion of 500 kt of TNT, while the Palabora 13-year seismic-energy release is equal to an underground explosion of 20 kt of TNT. The atom bomb that destroyed Hiroshima was equal to explosion of 20 kt of TNT. In reality the amounts of the total energy released are much higher because the seismic efficiency is only 0.5%. Figure 2.5 illustrates the locations of seismicity magnitude 3.5 and above, from the beginning of 1971 until the end of 1999 in the Klerksdorp area. During this time period, there were 673 such events, so there were 3 such events per month on average.

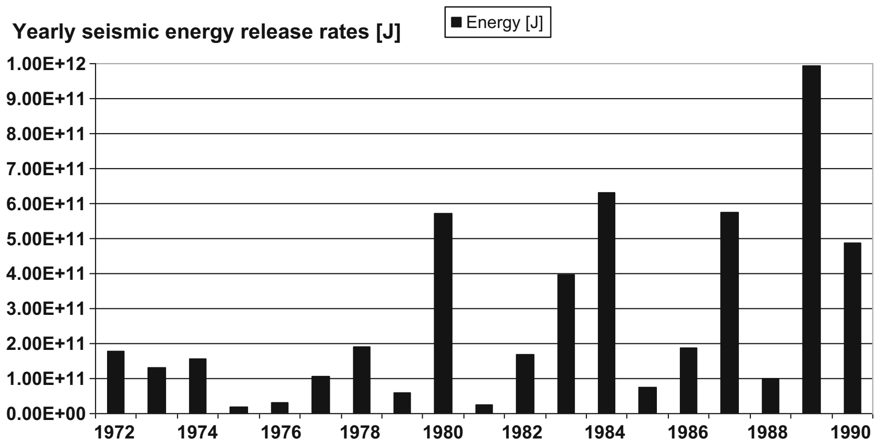

Fig. 2.4 Yearly seismic energy release rates

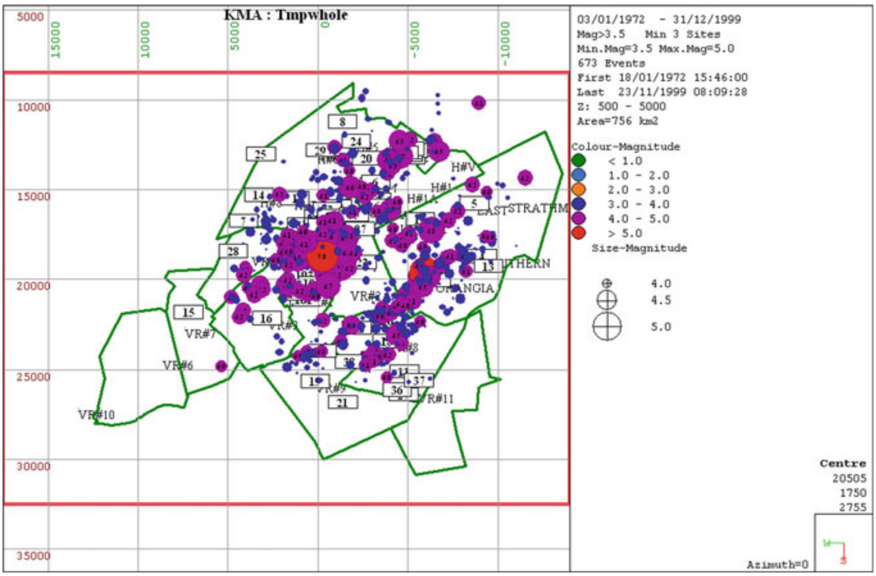

Fig. 2.5 Seismicity of magnitude 3.5 and above

Figure 2.6 illustrates the locations of seismicity magnitude 4.0 and above from the beginning of 1971 until end of 1999 in the Klerksdorp area. During this time period, there were 144 such events, so there were 0.7 such events per month (or two such events every quarter) on average. Total energy released by seismic event magnitude 4.0 is close to 3.6E + 13 J which is an equivalent of an underground explosion of 100 kt of TNT (five times the Hiroshima atom bomb).

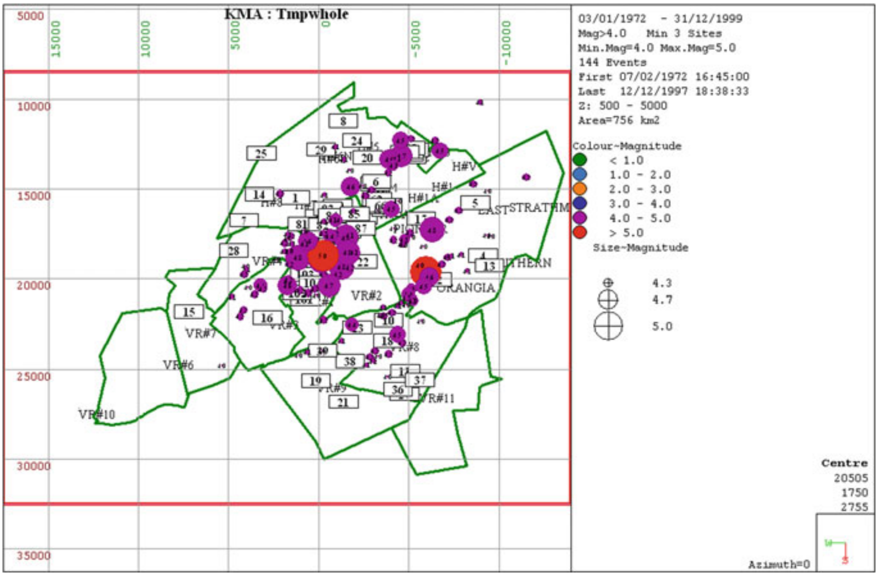

Fig. 2.6 Seismicity of magnitude 3.5 and above

During 1992, I used the seismicity recorded between June 1991 and June 1992 to estimate the probability of an accident due to seismicity. For this estimate, I used the 24-h number distribution of the underground working force. I was amazed to find out that, during the day shift, there were more than 24,000 people working underground. According to information from the internet, during 2011, the total population of Phalaborwa was 13,108. Figure 2.7 illustrates the 24-h distribution of people working underground at Vaal Reef during 1992. These numbers include

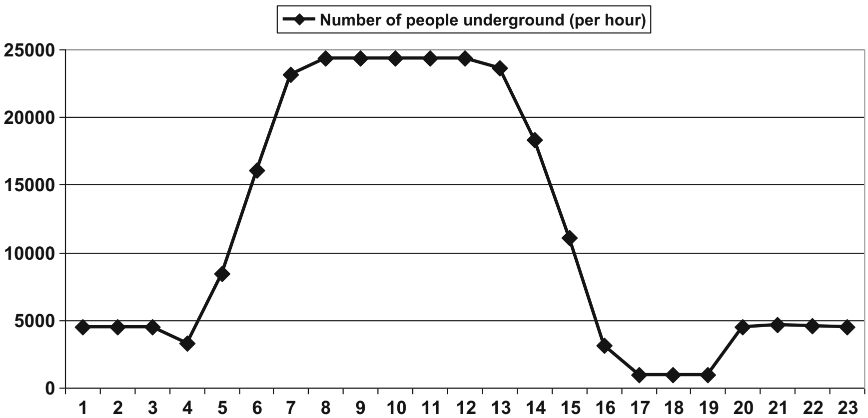

Fig. 2.7 Number of underground workers per hour at Vaal Reefs

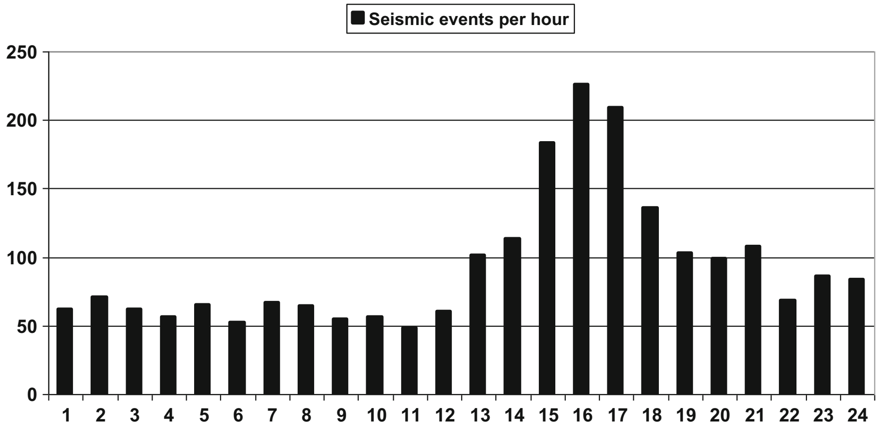

Fig. 2.8 24-h distribution of seismicity

data from No. 1 Shaft, No. 2 Shaft, No. 3 Shaft, No. 4 Shaft, No. 5 Shaft, No. 8 Shaft, and No. 9 Shaft. For the calculation, I used the 24-h distribution of seismicity and the 24-h distribution of released seismic energy.

Figure 2.8 illustrates the distribution of seismicity per hour and is based on a 13-month period (from 1 June 1991 to 30 June 1992) in which 2237 events of moment magnitude above 1.0 were recorded. The peak in the number of seismic events starts at 14:00 and ends at about 18:00 and is directly correlated with the blasting time. This is also the time when the minimum number of workers was underground. Figure 2.9 illustrates the seismic energy releases per hour. For comparison, the distribution of the number of events is also shown by this figure. The most interesting and important conclusion gathered from Fig. 2.9 is that the peak values for those two distributions do not coincide with each other. While the peak number of events per hour is connected directly with the blasting time, the peak amount of energy released per hour comes seven hours later (between 22:00 and 23:00). There are in fact three distinguishable peaks in the energy distribution. The first one that coincides with the peak of the number of events per hour, between 15:00–16:00, the second one between 20:00 and 21:00, which is twice as big as the first one; and the third main one between 22:00 and 23:00, which is 5.5 times as large as the first one.

From Fig. 2.9, it is evident that blasting on its own triggers many events, but most of them are relatively small ones; their number is high, but associated with relatively low amounts of released energy. It seems that there is an "ageing" period of about seven hours after which the high-energy release events do occur. This peak in released energy occurs when about 4500 workers on the night shift were underground.

Figure 2.10 illustrates how, during the day, the probability of a seismic-related accident changes. This probability was calculated as a function of the number of

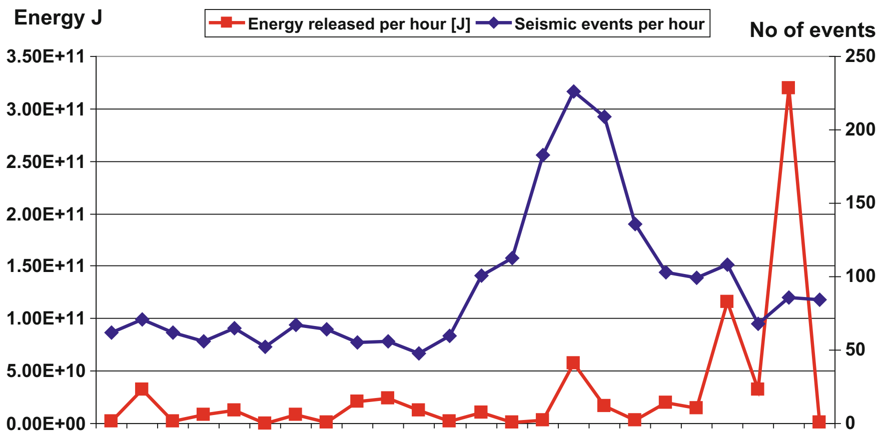

Fig. 2.9 24 h distribution of seismic energy and number of events

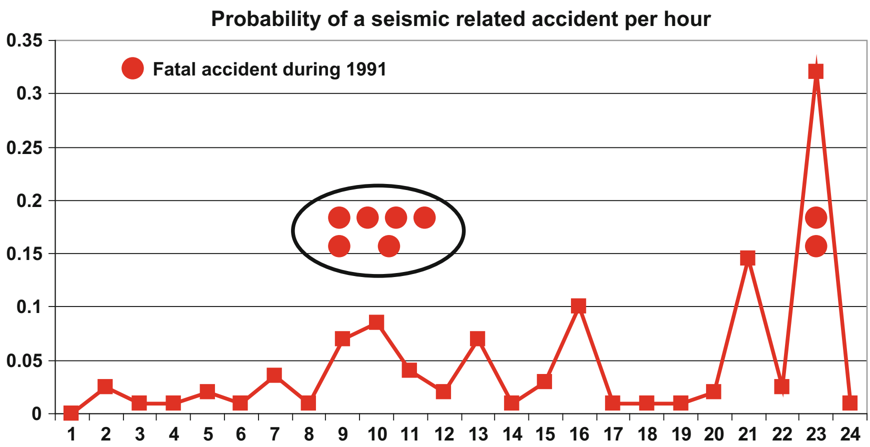

Fig. 2.10 Probabilities of seismic related accident

people per hour working underground, the number of seismic events, and the amounts of released seismic energy per hour. There are five distinct peaks:

First one between 9:00 and 10:00
Second one between 12:00 and 13:00
Third one between 15:00 and 16:00
Fourth one between 20:00 and 21:00
Fifth one between 22:00 and 23:00

Of these five probability peaks, the lowest one is the one between 12:00 and 13:00. The next one in size is the one between 09:00 and 10:00; then there is the one

Table 2.10 Probability peaks values

Peak	Hour	Probability value
1	Between 9:00 and 10:00	0.09
2	Between 12:00 and 13:00	0.07
3	Between 15:00 and 16:00	0.10
4	Between 20:00 and 21:00	0.14
5	Between 22:00 and 23:00	0.32

between 15:00 and 16:00; then the one between 20:00 and 21:00. The biggest one is between 22:00 and 23:00. Table 2.10 lists the probability values of these peaks.

The first peak is associated mainly with the high number of people working underground. The second peak is connected with the increase in the degree of seismicity, as well as with a high number of people still underground. The third peak is related to the increase in the number of events due to blasting. The last two peaks are related to the increase in the amounts of released seismic energy. Figure 2.10 also indicate the hours of the seismic-related fatalities during the first six months of 1991. These fatal accidents concentrate only in two short periods of the day, i.e., between 09:00 and 12:00 and then between 21:00 and 23:00. It is clear that the first concentration of fatalities is connected with the highest number of people for the day working underground, while the second is directly connected to the amount of released energy.

This analysis by its nature deals with a very delicate matter related to underground safety, but the danger of a seismic-related accident is a reality. Due to the nature of the input data based on facts, the results are more than just a pure mathematical exercise. From the presented analysis, it appears that the most dangerous hours are during the night shift between 20:00 and 23:00. In these three hours, there are a relatively high number of people in the underground working faces (4500), and, unfortunately, those are also the hours when the events associated with high-energy release take place. It must be clear that the probability of a seismic-related accident never drops to zero during the 24-h time period; it only varies from hour to hour. This means that an accident might happen at any one of these hours and that there are some hours in which its probability is higher than at others.

2.5 Upgrade of the Klerksdorp Regional Seismic Network

The network in the Klerksdorp area that was started in 1971 was established in order to understand 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. 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, e.g., by Gay et al. (1984) and O'Ferrall (1986). Seismic information was also used for planning and mining-shaft pillars, e.g., Emmenis and O'Ferrall (1971) or van der Heever and O'Connor (1994). The system was capable of informing management where the event had taken place within a 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 forty 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 had 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 as documented by van der Heever (1982) and Rorke and Roering (1984). By the beginning of 1990, significant progress had been made, not only in the 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 the evaluation of underground hazard. The accumulated experience from several mine networks (Lawrence 1984; Brink and Mountford 1984; Waldeck 1990; Mendecki et al.'s 1990; Flannigan and Hewlett 1988; van der Heever 1989; Patric and Kelly 1989; COMRO 1988a; Hewlett and Flannigan 1989; Brink 1990) made it clear that the time of analogue technology in this application was over.

Mine requirements from a seismic network have also progressed from passive to more active methods of assessing the underground hazard associated with seismicity. Mine management needs included:

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, e.g., for situating pillars along an active fault or for support design
4. 24-h management information service, for rescue and opening-up operations
5. Database 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 to all small events (down to magnitude 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. 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 network's central site as close as possible to the Rock Mechanics Department. The new site was located close to No. 1 Shaft, Vaal Reefs, in the same building as the main office of the Vaal Reefs Rock Engineering. By end of 1988 and the beginning of 1989, there were three regional mine seismic systems in operation; the DIGINET (later known as the Integrated Seismic System—ISS) in the Free State Goldfield, the "GENTEL" (Genmin Triaxial Event Locator) developed for Genmin Gold Mines; and the PSS (Portable Seismic System) developed by Chamber of Mines Research Organisation (COMRO). One of the three systems had to be chosen for the upgrade of the Klerksdorp Regional Seismic Network. The "GENTEL" system was eliminated because at that time it worked only as a single, stand-alone system, and it would be quite complicated from a technical point of view to network such single units into a regional system. It would require a significant amount of development and testing, and it would take at least two years to achieve some results. This left the remaining two systems, the PSS and ISS. The PSS system had all the basic limitations of analogue transmission, while the ISS system offered digital transmission and distributed intelligence. Digitization of the seismic data at the site of the transducer, plus the ability to accommodate the wide dynamic range (above 120 dB), could not be accomplished with high precision by any analogue transmission system. At that time, the ISS system also had another advantage over the PSS system, that is, its very advanced software and the hardware components were of an "off- the-shelf" type. The significance of PC architecture as the basis for seismic systems was postulated by Green (1990). There were two more important factors that helped to turn the decision in favour of the ISS system. The first one was that it was already in operation at Anglo American Corporation mines in the Orange Free State and secondly that Vaal Reefs had available a mainframe computer that could be used to run the network. In this way, the Anglo American Corporation (AAC) started a process of standardization of their seismic networks, in regards to hardware and software.

In April 1989, the Klerksdorp Mine Managers Association gave its approval to go ahead with upgrading the Klerksdorp Regional Seismic Network with the ISS system. This approval was connected with making the capital available, which was to be divided between all mines. The management of this project is described by van Wyk and Coggan (1990).

As the existing network configuration was good, the existing sites were used in the upgrade in order to minimize the costs. The newly upgraded system first started to collect seismograms in May 1990, and the official opening took place on 3 September 1990. Figure 2.11 presents an article from the Vaal Reefs Divisional

Seismic network updated

The revamped Klerksdorp Mine Manager's Association seismic network was officially commissioned on Vaal Reefs this month by Mr R G Tarr.

The network was originally situated near Margaret Shaft on Stilfontein Gold Mine but became outdated with the advent of digital data storage of seismic data. According to Mr Stefan Glazer, Seismologist on Vaal Reefs, the old system made use of analog transmissions from underground geophones and these signals were noisy which prevented accurate information about seismic events being recorded.

The new digital system, known as the Integrated Seismic System, was developed by AAC TDS in Welkom and gives far more accurate measurements of seismic events. It is likely to become the industry standard of the future.

Mr Glazer said the reason for moving the network from Stilfontein to Vaal Reefs was to overcome the shortcoming of being located on the edge of the mining area and consequently far away from some geophones. Vaal Reefs is centrally situated both for present day mining operations and for future expansion in this area. He also said that with the new system, the seismic network would be able to pinpoint the really hazardous areas before a large seismic event occurs. The system will also assist in the design of better stope support and should improve the percentage of reef extraction near geological discontinuities.

Mr Glazer said ultimately the Integrated Seismic System was a tool to provide the information that would be used to improve safety and increase productivity on all deep level mines.

Mr R G Tarr, Chairman of the KMMA Seismic Liaison Committee, cuts the ribbon to officially open the new Regional Seismic Network on Vaal Reefs. Looking on from left to right are Mr H Kolbe, Manager Technical Services at Hartebeestfontein GM, Mr S N Glazer, Seismologist on Vaal Reefs, Dr A Mendecki, Anglo American TDS in Welkom and Mr J J van WYk, Regional Head of Rock Mechanics on Vaal Reefs.

Fig. 2.11 Opening of the new seismic network

News (1990). I have replaced the black and white photograph with a colour one from my personal collection. By the end of 1992, the Klerksdorp Regional Seismic System went through one more upgrade. This time, the upgrade was made to its central-site facility. The Perkin-Elmer mainframe computer was replaced by a UNIX-based System u6000/60. The other big change that took place was the establishment of a network link between the Seismic Section and the Rock Mechanics Department at Vaal Reefs and Hartebeestfontein GM. This indicates that only two years after upgrading from an analogue to a digital system, the demand for seismic data to be used in the recommendations of the Rock Mechanics Department became so great that it could justify such a network. During 1991 and 1992, several PC based programs were developed at Vaal Reefs.

This software was still used at the end of the 20th century, not only for graphical display of seismic data but mainly for interpretation purposes. At that time, the interpretation techniques included the use of apparent stress index, the concept of which is described in Chap. 3. With increased use of data by the rock-engineering staff, and with the development of interpretation methods came the request for more accurate information. This was achieved by improving the configuration of the network and installing additional stations at selected areas, especially at Vaal Reefs, with an additional capital expenditure required at Vaal Reefs. For this reason, it was necessary to create the Vaal Reefs Seismic Project with its own capital and working costs. By May 1993, the Klerksdorp Regional Seismic Network had a complement

Table 2.11 Number of seismic stations Klerksdorp Regional Network 1990–1993

Mine	End of 1990	End of 1991	End of 1992	End of 1993
Vaal Reefs	15	15	22	25
Hartebeestfontain	10	10	10	10
Buffelsfontain	6	6	6	7
Stilfontein	1	1	–	–
Total	32	32	38	42

Note Stilfontein GM closed its operations by the end of 1992

of five staffers (one seismologist, two technicians, one technical assistant, and one computer programmer). At the same time, the Vaal Reefs Seismic Project employed additionally one seismologist and one technical assistant. Table 2.11 indicates the number of seismic stations of the Regional Seismic Network between 1990 and 1993.

Figure 2.12 illustrates the configuration of the network recording stations at the end of 1993.

Table 2.12 lists numbers of events recorded by the Klerksdorp Regional Seismic Network from the beginning of 1990 to the end of 1993. This table is a continuation of data presented by Table 2.5.

Note the increase in the network sensitivity from year to year, which is evident when comparing the numbers of recorded events of M_L up to magnitude 2.0 (Fig. 2.13). After the completion of the upgrading, the number of recorded events increased from year to year.

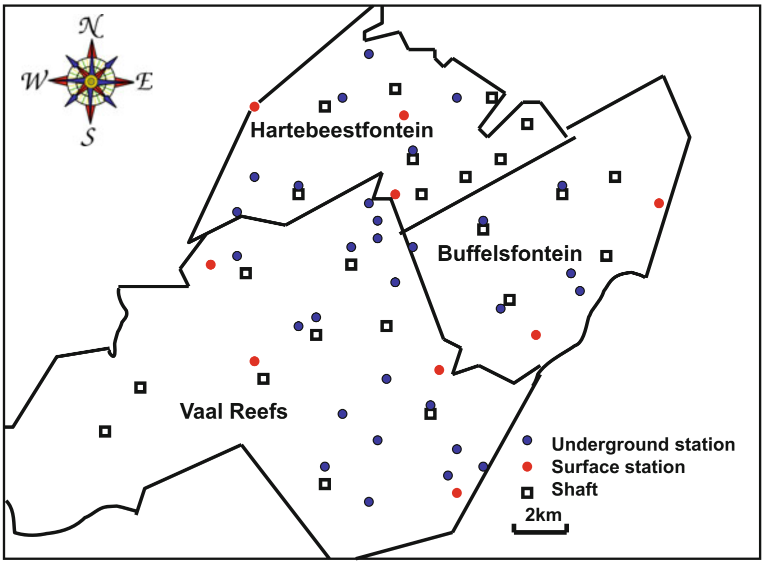

Fig. 2.12 KMMA Regional Seismic Network configuration by the end of 1993

Table 2.12 Number of events recorded by the Klerksdorp Regional Seismic Network

Year	Below 1.0	1.0–1.9	2.0–2.9	3.0–3.9	Above 4.0	Total
1990	193	1066	432	87	2	1780
1991	2348	2725	814	121	3	6011
1992	4482	2815	793	118	0	8208
1993	6975	2610	625	102	2	10,314

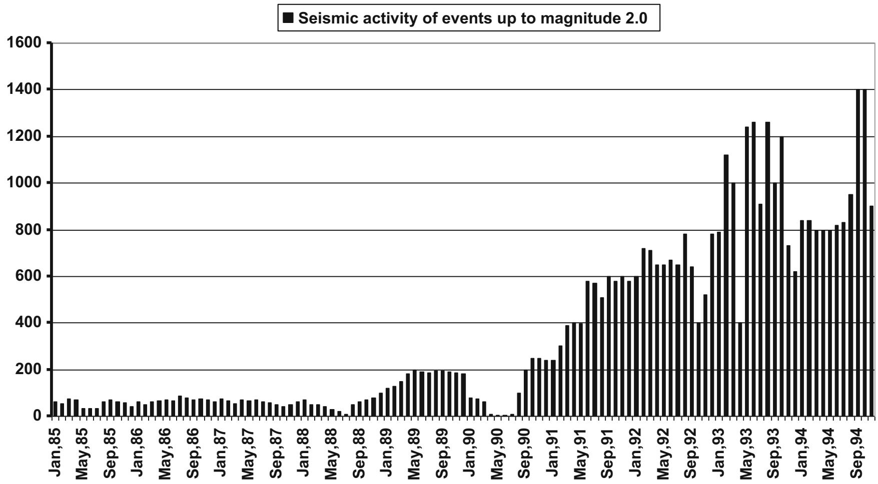

Fig. 2.13 Monthly seismicity (up to M_L = 2.0) rates between 1985 and 1993

It is interesting to compare data from Table 2.12 with that in Table 5.4 of Sect. 5.4, which describes the network performance up to May 1997. Whereas, for the entire year of 1993, the network recorded about 10,000 events, this number for May 1997 alone was nearly 25,000 events. As this increase is only in the number of small events, these two figures indicate how much the network had changed during these years.

2.6 Use of Seismic Data in the Calculation of Support Resistance for Rock-Burst Conditions at Vaal Reefs

"An Industry Guide to Methods of Ameliorating the Hazards of Rockfall and Rockbursts" (COMRO 1988b) was published at the request of the Association of Mine Managers of South Africa. It provided a summary of the state of the art of rock engineering in South African tabular hard-rock mining conditions; conditions under which rock fall and rock burst occur vary considerably between mining districts and even within individual mines. It therefore follows that the setting of individual standards based on local conditions remains the responsibility of management and staff of individual mines. For this reason, the design outlined in the rock-fall and rock-burst guide should be adopted throughout, but, where additional local information is available, it should be incorporated for design purposes. When calculating the support resistance (R_s) for rock-burst conditions, the following factors have to be considered:

– Peak ground velocity (V)
– Thickness of the hanging wall beam involved (h)
– Displacement of the hanging wall versus maximum tolerable prop displacement (d).

The guide provides the following values:

Hanging wall beam thickness	h = 3 m
Peak ground velocity	V = 3 m/s
Dynamic displacement	d = 0.3 m

Support resistance (R_s) is then calculated from the following formula (COMRO 1988b)

$$\mathrm{Rs} = \left(1 + \mathrm{V}^2/2\mathrm{gd}\right)\rho\,\mathrm{gd}$$

where

ρ 2700 kg/m^3 (rock density)
g 9.81 m/s^2

With this input the support resistance R_s = 201 kN/m^2.

However, at Vaal Reefs, there were two values that were found to be different to those that were provided by the guidelines. The first value was the beam thickness, where a value of 2 m was found to be more representative for the majority of falls of ground and rock bursts at Vaal Reefs. The second value was the peak ground velocity (PGV). One of the first tasks of the upgraded Regional Seismic Network was to calculate the experienced values of peak ground velocities for local conditions, so that they could then be used for calculating support resistance for rock-burst conditions (Glazer 1998). The value of the peak ground velocity multiplied by the hypocentral distance seems to depend on magnitude. The least-squares regression line given by McGarr et al. (1981) was determined on the basis of twelve mine events in the East Rand Proprietary Mines, for tremors with magnitudes between −1.0 and 2.6 for hypocentral distances between 50 and 1600 m.

$$\mathrm{Log}[\mathrm{R} \times \mathrm{V}(\mathrm{cm/sec})] = 0.57\mathrm{M_L} + 3.95$$

where:

R hypocentral distance (cm)
V peak velocity (cm/s)
M_L local magnitude.

Studies aiming at finding the relationship between the local magnitude, the hypocentral distance, and the peak ground velocity were done at the Klerksdorp Regional Seismic Network. Based on more than 2000 direct measurements, the following least-square regression relationship was established (Fig. 2.14).

$$\mathrm{Log}[\mathrm{R(m)} \times \mathrm{V(m/s)}] = -1.97 + 0.98\mathrm{M_L}$$

where

R hypocentral distance (m)
V peak velocity (m/s)
M_L local magnitude.

This equation, based only on values measured in the Klerksdorp Gold Mines, was established for magnitudes from 0.5 to above 4.0 for hypocentral distances ranging from 500 to more than 10,000 m. To assess the seismic hazard in terms of ground motion velocity, it must be related to the ground motions within the actual source regions of the mine tremors where the gold mining operations take place. Up to that time, there were no known measurements done in the near field. All near field estimations were based on extrapolations of far-field relations. The database used to establish the local relation consisted of 2296 seismic events. Of this number, only three had a magnitude of over 4.0 (0.13%), and 106 of them had a magnitude

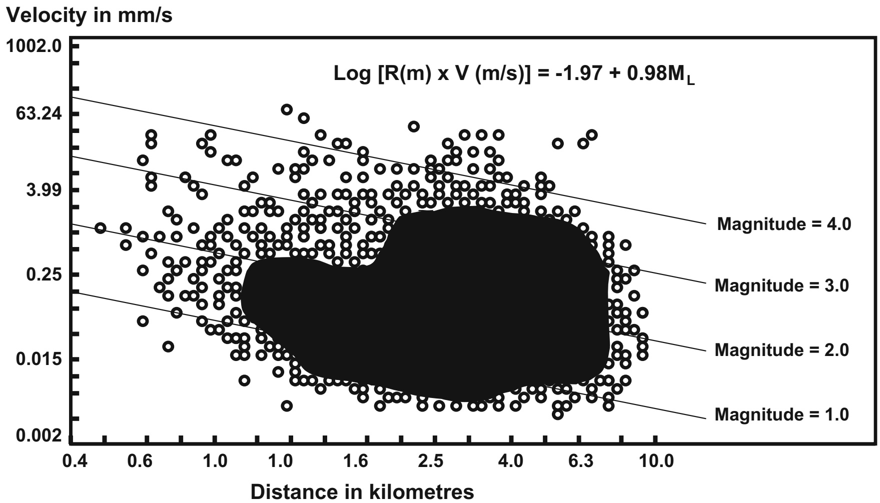

Fig. 2.14 Distance versus maximum ground motions (1991)

Table 2.13 PGV [m/s] for the Klerksdorp area resulting from the two formulas

Distance (m)	M_L = 3.0		M_L = 3.5		M_L = 4.0	
	McGarr	Local	McGarr	Local	McGarr	Local
50	0.91	0.19	1.76	0.60	3.40	1.80
100	0.45	0.09	0.88	0.30	1.70	0.90
150	0.30	0.06	0.59	0.20	1.10	0.60
200	0.23	0.04	0.44	0.15	0.85	0.45

of more than 3.0 (4.6%). If the regression lines based on McGarr's and local formulas were extrapolated to the near field, the following values of peak ground velocities will result (m/s).

From Table 2.13, the ratio between the resulting values of PGV according to the two formulas is as follows:

$$\begin{aligned} &\text{For } M_L = 3.0 \quad \text{it is } 0.2 \\ &\text{For } M_L = 3.5 \quad \text{it is } 0.3 \\ &\text{For } M_L = 4.0 \quad \text{it is } 0.5 \end{aligned}$$

Taking into account that over 99% of the recorded events were of magnitude below M_L = 4.0, it is a fair assumption that peak ground velocities of up to 2.0 m/s are the maximum that can be expected in the Klerksdorp area—for this range of magnitudes. From Fig. 2.12, it is evident that the ground velocities as experienced in the Klerksdorp area are well below the value of 3 m/s (COMRO 1988b), and, in fact, the maximum PGV recorded by that time was below 0.25 m/s. According to McGarr and Bicknell (1990), seismic events above magnitude 3.0, which involve slip across a major fault, have larger source dimensions and lower levels of ground motions in the Klerksdorp area than on the East Rand. Based on these results, in 1991, it was decided to use a design velocity of 2.3 m/s (which was an over-estimation). This value, together with hanging wall beam thickness h = 2 m, resulted in a support-resistant value of 100 kN/m^2, which was half of the recommended value. This lower support-resistant value made possible saving of a lot of money. On the basis of two types of local observations, one being the fall of ground and the other from a seismic network, the following recommendations for face-area support in rock-burst conditions were made and implemented in 1991:

- Support resistance of 100 kN/m^2
- Two rows of 40-ton rapid yield hydraulic props
- In order to achieve the required 100 kN/m^2, a rapid yielding hydraulic prop spacing of 1.5 m on dip and strike was recommended

The evaluation of peak ground velocity in the Klerksdorp area was repeated with more input data in 1996. This time, the findings of Hedley (1990) and Butler and van Aswegen (1993) were used. They found that it is better to use seismic energy instead of local magnitude. Radiated seismic energy is directly dependent on the velocity of ground motion, while any other event parameter containing seismic moment is dependent on the low-frequency content of the ground motion. The relation used to calculate the peak ground velocity has the following, from (Butler and Van Aswegen 1993):

$$\mathrm{Log(V)} = \mathrm{A} \times \text{strength parameter} + \mathrm{B}[\log(\mathrm{R})] + \mathrm{C}$$

where

V	Peak ground velocity (PGV)
R	Hypocentral distance
A, B, C	Constants
Event strength parameter	magnitude, log energy, or log moment of seismic events.

As only relatively large seismic events can result in underground damage, then for analysis purposes, only events above M_L = 1.0 were taken into consideration. For this analysis, the following criteria were established:

Events recorded between 1 January 1995 and 30 June 1996 (18 months)
Events above local magnitude M_L = 1.0
Events recorded by a minimum of five seismic stations
Hypocentral distance of source to station below 1000 m

Figure 2.15 shows the resulting velocity-versus-distance relationship for various energies. From this graph, the following equation describing the relationship between the PGV, hypocentral distance, and energy is derived:

$$\mathrm{Log(V)} = 0.469\log(\mathrm{E}) - 1.363\log(\mathrm{R}) - 1.999$$

where

V is expressed in m/s
R is expressed in metres.

Figure 2.15 shows the relationship of energy versus seismic moment for events with local magnitude M_L > 1.0. From this figure the following energy-versus-seismic-moment relationship was obtained:

$$\mathrm{Log(E)} = 1.547\log(\mathrm{M_O}) - 11.245$$

where

E is expressed in J
M_O is expressed in Nm.

The relationship between local magnitude M_L and seismic moment and energy is then as follows:

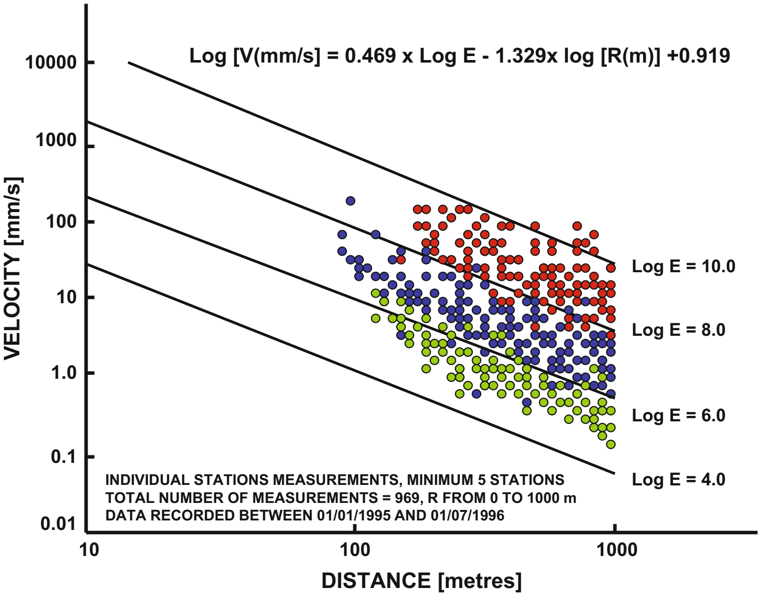

Fig. 2.15 Distance versus maximum amplitude of ground motions (1996)

$$\mathrm{M_L} = 0.333\log(\mathrm{M}) + 0.263\log(\mathrm{E}) - 3.613$$

$$\text{and finally: } \mathrm{Log(E)} = (\mathrm{M_L} + 1.192)/0.478$$

A crude fit of two straight lines over the data in Fig. 2.16 was made in order to establish an envelope around the best-fit line. In this way, an estimate of error for

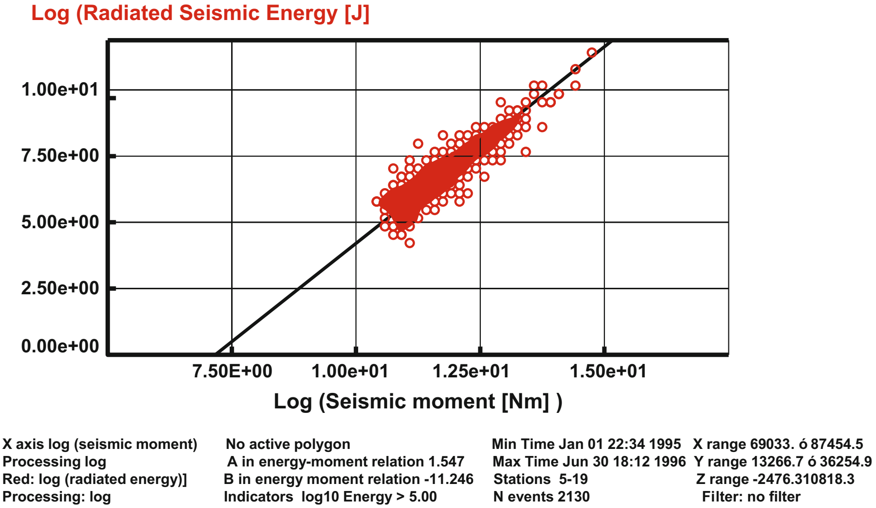

Fig. 2.16 Energy-moment relation for events above 1.0

Table 2.14 PGV values for different local magnitudes and hypocentral distances

Distance (m)	M_L values		
	1.7–2.3	2.8–3.2	3.8–4.1
100	2.6 cm/s	24.4 cm/s	2.3 m/s
200	1.0 cm/s	9.5 cm/s	0.9 m/s
500	0.3 cm/s	2.7 cm/s	0.3 m/s

the moment value associated with the specific energy value could be made. As a result, a variation in local magnitude associated with specific energy could be established.

Table 2.14 shows the resulting PGV values for different M_L ranges for different hypocentral distances.

It is interesting to note that, while in 1991 (Fig. 2.13), the smallest hypocentral distance was about 500 m, this value was about 100 m in 1996 (Fig. 2.14). This was due to fact that during 1996 the network had more recording stations than during 1991 (see Chap. 5 for more details). From January 1995 to July 1996, only 12 events with local magnitude above 4.0 took place (the highest being $M_L = 4.3$). For this reason, it is assumed that the derived relationship is valid for the Klerksdorp mining area, and V = 2.3 m/s should be used for support-resistance calculations. It is interesting to note that McGarr (1993) concluded that the rapid-yielding hydraulic props used in all of the Witwatersrand gold fields should be designed to withstand ground velocities of 4 m/s. However, Vaal Reefs data and the experience of more than five years indicated that 2.3 m/s was sufficient for local conditions.

2.7 Summary and Conclusions

Seismicity in the Klerksdorp area is mining induced. It appeared only when the mines started to operate at more than 1500 m below the surface. With time, the size of this seismicity increased, and it resulted not only in damage to underground structures but in accidents involving miners who lost their life or were injured. This was not new as rock bursts and rock falls had earlier posed a serious problem in gold mines of the Witwatersrand, practically since the beginning 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 remained as serious as ever, mainly as a result of the increasing extent and depth of mining. However, by 1977 it was realised that most of the information that had been accumulated was dispersed throughout a great number of scientific and technical publications and in the proceedings of many conferences, and some of the important practical issues concerning implementation ha d not been published or implemented in the industry. For this reason, it became 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 the Research Advisory Committee, the Technical Advisory Committee, the Association of Mine Managers and representatives of the rock-mechanic engineers. This committee published in 1977 "An Industry Guide to the Amelioration of the Hazards of Rockburst and Rockfalls". 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 that might be more active due to geological features or inherent stress

In 1971, the Klerksdorp Regional Seismic Network was established as a joint venture between the Chamber of Mines and the four mines in the area. From the start, this network was under the guardianship of Klerksdorp Mine Managers Association. It was still so when I arrived in Klerksdorp in 1988. These managers were taking real interest not only in the seismic activity but in what can be done to alleviate the problem of seismic hazards. Up to my arrival, a lot had been done concerning this matter. Records from this seismic network were used to devise a number of practical strategies for mining in seismically active mines. These strategies are still in use today as nothing better could be developed. It seems that, with the development of digital technology, the Chamber of Mines and South African universities input into mine-seismology progress has become less significant. During the early 1990s, a lot of technical specialists hoped that the introduction of digital seismic networks would improve the situation, as far as the seismic hazard is concerned. A universal remedy as such does not exist and that was also the case with the digital networks. Yes, they could record but something had to be done so that this recorded data could be used for practical purposes. Today it seems that, with time, the mining industry lost the already existing knowledge about mine-induced seismicity and then did not benefit much from the new technology. Proof of this situation is easy to document. A seismic event with a local magnitude of $M_L = 5.3$ occurred at 12:15 on 9 March 2005 at DRDGOLD's NorthWest Operations in the Klerksdorp district. In response, the Chief Inspector of Mines initiated an investigation into the risks to miners, mines, and the public arising from seismicity in gold-mining districts. Why? This type of investigation had already been done. The last investigation in 2006 reached conclusions that are well known to professional mine seismologists. This indicates that at present the South African mining industry has no professional mine seismologists who can be employed by the mines.

References

Antrobus ESA, Brink MC, Caulkin J, Hutchison RI, Thomas DE Graan vJA, Vilioen JJ (1986) The Klerksdorp Goldfield. In: Anhaeusser CR, Maske (eds) Mineral deposits of Southern Africa I. Geological Society South Africa, pp 549–598

Brink AvZ (1990) Application of microseismic system at Eastern Deep Levels. In: Faihurst C (ed) Rockburst and seismicity in mines. Balkema, Rotterdam, pp 355–361

Brink AvZ, Mountfort PI (1984) Feasibility studies on the prediction of rockburst at Western Deep Levels. In: Gay NC, Wainwright EH (eds) Rockburst and seismicity in mines. Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 317–325

Brown A (1983) Golden Heritage. Published by the Author

Bruns L (1977) The birth of a complex. Western Reefs 1933–1971, Perskor, Johannesburg

Butler AG, van Aswegen G (1993) Ground velocity relationship based on a large sample of underground measurements in two South African mining regions. In: Young P (ed) Rockbursts and seismicity in mines. Balkema, Rotterdam, pp 41–49

COMRO (1977) An industry guide to the amelioration of the hazards of rockburst and rockfalls. Compiled by the High-Level Committee on Rockburst and Rockfalls. Chamber of Mines of South Africa, Johannesburg

COMRO (1988a) The portable seismic system. Application Report No 21, Chamber of Mines of South Africa, Johannesburg

COMRO (1988b) An industry guide to methods of ameliorating the hazards of rockfalls and rockburts. Users Guide No 12, Chamber of Mines of South Africa, Johannesburg

Cook NGM (1962) A study of failure in rock surrounding underground excavations. PhD thesis, University of the Witwatersrand, Johannesburg

Durrhein RJ, Anderson RL, Cichowicz A, Ebrahim-Trollope R, Hubert G, Kijko A, Ortleepp WD, van der Merwe N (2006) Investigation into the risk to miners, mines and the public associated with large seismic events in gold mining districts, vol 1. Requested by: Ms M Hermanus, Chief Inspector of Mines, Department of Minerals and Energy, South Africa www.csir.co.za/websource/…/Seismic/DMEInvestigationlargeseismiceventsvol1.pdf

Emmenis RJ, O'Ferral MRC (1971) The extraction of Toni Shaft pillar. Association of Mine Managers of South Africa, Papers and Discussions, Chambers of Mines of South Africa, Johannesburg, pp 459–491

Fernandez LM, Guzman JA (1979a) Seismic history of Southern Africa. Seismology Series No 9, Geological Survey, Pretoria

Fernandez LM, Guzman JA (1979b) Earthquake Hazard in Southern Africa. Seismology Series No 10, Geological Survey, Pretoria

Fernandez LM, Labuschagne PGA (1979) Catalogue of earthquakes in Southern Africa and surrounding oceans for 1976. Seismology Series No 8 Geological Survey, Pretoria

Fernandez LM, van der Heever P (1984) Ground movement and damage accompanying a large seismic event in the Klerksdorp district In: Gay NC, Wainwright EH (eds) Rockburst and seismicity in mines. Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 193–198

Finsen WS (1950) The statistics of Witwatersrand earth tremors 1938 to 1949. Unions Obs Circ. 110, Johannesburg, pp 444–456

Flannigan WC, Hewlett P (1988) The computer basis for a regional seismic monitoring system. In: SANGROM symposium: rock mechanics in Africa, Swaziland

Gane PG (1939) A statistical study of the Witwatersrand earth tremors. J Chem Metall Miner Soc S Afr 40

Gane PG, Hales AL, Oliver MA (1946) A seismic investigation of the Witwatersrand earth tremors. Bull Seismol Soc Am 36:49–80

Gay NC, Spencer D van Wyk JJ, van der Heever PK (1984) The control of geological and mining parameters on seismicity in the Klerksdorp gold mining district. In: Gay NC, Wainwright EH (eds) Rockburst and seismicity in mines. Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 107–120

Gibowicz SJ, Kijko A (1994) An introduction to mining seismology. Academic Press, New York

Glazer SN (1998) Practical applications of stress index and other seismological parameters in combating rockburst hazard in deep gold mine of Vaal Reefs, South Africa. PhD thesis submitted to the Department of Geology, Geophysics and Environmental Protection, University of Mining and Metallurgy, Krakow, Poland, June 1997 (in English)

Glazer SN (2016) Mine seismology: data analysis and interpretation. Palabora Mine caving process as revealed by induced seismicity. Springer International Publishing, Switzerland. doi:10.1007/ 978-3-319-32611-5

Green RWE (1990) Keynote lecture: instrumentation networks for observation on mine-induced seismicity. In: Fairhurst C (ed) Rockbursts and seismicity in mines. Balkena, Rotterdam, pp 165–169

Guest H (1938) Klerksdorp's fifty years of mining. Published by Klerksdorp Mine Managers Association

Guest H (1987) Klerksdorp's 100 years of mining. Published by Klerksdorp Mine Managers Association

Gutenberg B, Richter CF (1956) Earthquake magnitude, intensity, energy and acceleration (second paper). Bull Seismol Soc Am 46:105–145

Hanks TC, Kanamori H (1979) A moment magnitude scale. J Geophys Res 84:2348–2350

Hedley DGF (1990) Peak particle velocity for rockbursts in some Ontario mines. In: Fairhurst C (ed) Rockbursts and seismicity in mines. Balkema, Rotterdam, pp 345–348

Hewlett P, Flannigan WC (1989) New development on the ISS. In: COMRO innovation in mining, development and application of new seismic technology for rockburst control. South African Nature Conservation Centre, Johannesburg

Joughin NC (1966) The measurement and analysis of earth motion resulting from underground rock failure. PhD thesis, University of Witwatersrand, Johannesburg

Kijko A, Sellevoll MA (1989) Estimation of earthquake hazard parameters from incomplete data files. Part I. Utilization of extreme and complete catalogues with different threshold magnitudes. Bull Seism Soc Am 79:645–654

Kijko A, Sellevoll MA (1992) Estimation of earthquake hazard parameters from incomplete data files. Part II. Incorporation of magnitude heterogeneity. Bull Seismol Soc Am 82:120–134

Lawrence D (1984) Seismicity in orange free state gold mining district. In: Gay NC, Wainwright EH (eds) Rockbursts and seismicity in mines. Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 121–130

McGarr A (1993) Keynote address: factors influencing the strong ground motion from mining-induced tremors. In: Young RP (ed) Rockburst and seismicity in mines. Balkena, Rotterdam, pp 3–12

McGarr A, Bicknell J (1990) Estimation of the near-fault ground motion of mining-induced tremors from locally recorded seismograms in South Africa. In: Fairhurst C (ed) Rockburst and seismicity in mines. Balkema, Rotterdam, pp 245–248

McGarr A, Green RWE, Spottiswoode SM (1981) Strong ground motion of mine tremors. Some implications for near-source motion parameters. Bull Seismol Soc Am 71:295–319

Mendecki AJ, van Aswegen G, Brown JNP, Hewlett P (1990) The Welkom seismological network. In: Fairhurst C (ed) Rockburst and seismicity in mines. Balkema, Rotterdam, pp 237–243

Midzi V, Zulu B, Manzunzu B, Mulabisana T, Pule T, Myendeki S, Gubela W (2015) Macroseismic survey of the Ml Orkney earthquake. J Seismol 19(19):741–751

Nell T (1935) The geology of the Klerksdorp-Ventersdorp area: an expansion of the geological map. Geological Survey South Africa, Pretoria

O'Ferrall RC (1986) Procedures for mining in the vicinity of faults and dykes in the Klerksdorp area. Colloquium: Mining in the Vicinity of Geological and Hazardous Structures. South African Institute of Mining and Metal, Johannesburg

Patrick KW, Kelly AM (1989) The COMRO seismic system: hardware and software. In: COMRO innovations in mining, development and application of new seismic technology for rockburst control. South African Nature Conservation Centre, Johannesburg

Rorke AJ, Roering C (1984) Source mechanism studies of mining-induced seismic events in a deep-level gold mine. In: Gay NC, Wainwright EH (eds) Rocburst and seismicity in mines, Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 51–56

Shapira A, Fernandez L, Du Plessis A (1989) Frequency-magnitude relationship of Southern Africa seismicity. Tectonophysics 167:261–271

Scheepers JB (1982) The Klerksdorp seismic network: monitoring of seismic events and system layout. In: Gay NC, Wainwright EH (eds) Rockbursts and seismicity in mines. Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 341–345

van der Heever PK (1982) The influence of geological structure and seismicity and rockburst in the Klerksdorp Goldfield. WSc dissertation, Rand Afrikaans University, Johannesburg

van der Heever PK (1989) Single station triaxial location systems. In: COMRO innovation in mining, development and application of new seismic technology for rockburst control. South African Nature Conservation Centre, Johannesburg

van der Heever PK, O'Connors TS (1994) The mining of a stressed deep-level shaft pillar. XVth CMMI Congress, South African Institute of Mining and Metal, Johannesburg

Waldeck MG (1990) The monitoring of seismicity and measures implemented to alleviate rockburst at Kloof—a division of Kloof Gold Mining Company Limited. In: Fairhurst C (ed) Rockbursts and seismicity in mines. Balkema, Rotterdam, pp 395–400

Webber SJ (1988) A comparison between the magnitude scales of the South African Geological Survey and the Klerksdorp Regional Seismic Network. Technical Note, Rock Mechanics Laboratory, Chamber of Mines of South Africa, Johannesburg

Whiteside HCM, Glasspol KR, Hiemstra SA, Pretorius DA, Antrobus ESA (1976) Gold in the Witwatersrand Triad. In: Coetze CB (ed) Mineral resources of the Republic of South Africa, Handbook 7, 5th edn. The Government Print, Pretoria, pp 39–73

Vaal Reefs Divisional News, vol 2, No 9, p 3, September 1990

Van Wyk JJ, Coggan JS (1990) Establishment of improved seismic monitoring facilities in the Klerksdorp area. In: Technical challenges in deep level mining. South African Institute of Mining and Metal, Johannesburg

Springer
http://www.springer.com/978-3-319-62352-8

Mine Seismology: Seismic Warning Concept
Case Study from Vaal Reefs Gold Mine, South Africa
Glazer, S.N.
2018, XV, 201 p. 100 illus., 91 illus. in color., Hardcover
ISBN: 978-3-319-62352-8