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Mine Seismology: Seismic Warning Concept

Case Study from Vaal Reefs Gold Mine, South Africa

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ISBN 978-3-319-62352-8 ISBN 978-3-319-62353-5 (eBook)
https://doi.org/10.1007/978-3-319-62353-5

Library of Congress Control Number: 2017952934

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Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

A wise man will receive warning, but a fool
will sooner be smitten in the face.
—Coverdale, Proverbs 10:8

I dedicate this book to all those who contributed towards mine seismology when it was based on analogue technology. At that time, being a seismologist analysing and interpreting data recorded by mine networks required not only sound knowledge but also exceptional commitment. It is not surprising that their research results are still valid today and are not replaceable by the today's research. My special appreciation goes to those that were associated with the Klerksdorp Mine Managers Association's Regional Seismic Network.

Preface

The events described in this book took place between the years 1990 and 2000 at the South African gold mine Vaal Reefs. My first book (Glazer 2016) describes my experience as a mine seismologist at Palabora Mining Company (PMC), a South African copper mine, from 2002 until 2013. These two periods of my life enabled me to make certain statements on the condition of mine seismology in South Africa as it stands at the end of 2016. Probably less controversial, my first conclusion is that there is a place for seismology in the mines. The problem is that most mining personnel are not convinced that there are any benefits from the use of seismic monitoring. The nonbelievers exist both among the mine managers and the technical staff. The former are sceptical because they must balance the costs and benefits, which is understandable because this is their job. On technical matters, they depend on technical staff. The latter, on the other hand, can be divided into those that know nothing and those that think that they know everything about mine seismology. In my over twenty years of being a mine seismologist, I have come across only two mining engineers who understood mine seismology. What I found strange was that very often the technical personnel were more concerned about saving money for the mine in the short term rather than investing in mine seismology for any future benefits. The reason for this situation is at least twofold.

Installation of the seismic network in the mine on its own doesn't introduce any immediate benefits. These come with time, but only when the seismic network is managed by a professional mine seismologist. That is the second part of the problem: there are no professional mine seismologists available to work at the mines. The mine manager as such is not interested in examining recorded seismicity in the back analysis mode. It doesn't matter if these back analysis examples are of a high standard or are pure fiction. They are about the past and of no help to the mine. What counts at the mine is production and what can make increase it and/or make it safer. That is why recorded seismic data has to contribute towards today's needs in the mine. And this can be done only when the professional mine seismologist is at the place where the action is, which is at the mine. If he is a professional seismologist, then he will be able to prove to the mine management that seismic monitoring benefits the mine. I know this from my experience. The sad part of the story is that it was often easier to convince a mine manager than a rock engineer. My best practical applications of mine seismology came when I was not related to the Rock Engineering Section. At Vaal Reefs I was working directly for the Klerksdorp Mine Managers Association, and at PMC the seismic network was part of the Cave Management Section. For sure, there must have been a reason for this.

I believe that most of the rock-engineering personnel employed by the mines (at least in South Africa) have no proper knowledge of mine seismology. Knowledge of any technical subject must be based on sound science. If not, then it is fiction, and it doesn't matter if this fiction is mixed with some science. It is still fiction. This fiction, when introduced into industry, awakens false expectations that cannot be achieved. This then degrades mine seismology as a science. As a result, mine management doesn't see any use for it. It will still purchase seismic systems and then appoint amateurs to operate them. In this way, they have done what a reasonable manager would do by installing the system. They are then doing what a good manager would do by reducing the working costs. As a result, there are plenty of operational seismic systems at the mines but there are no practical results. Lack of those convinces the industry that mine seismology is of no use.

At the present time, mine seismology is in serious regression. This applies to theory and practice. The good news is the recording hardware for digital seismic systems. It is good and, what is even more important: it has been tested in practice. We know that the seismic-system hardware operates in difficult conditions, and there is no problem with this part of mine seismology. The setback starts with the use of the recorded data. With the introduction of digital seismic recording, it was assumed that all or most of the existing theory is wrong and that it has to be rewritten from the beginning. From the start, this was not a concept to test but was treated as an axiom. The mining industry was bombarded with new ideas and concepts. It became unclear what is a concept that still requires testing and what is a pure concept. New theory was presented as being very complex and wrapped in terminology that was difficult to understand. In this way, mine seismology that, during the analogue age, had sound theory that resulted in numerous practical applications became a "black box". Under such conditions, mine after mine outsourced management of its seismic systems. The situations became ridiculous. The contractor assumed the role of deciding what the mine requirements from seismic monitoring might be. In this way, mine seismology and the mine industry went in two different directions.

I hope that this book will be read not only by those that are interested in mine seismology but also by the present and future technical mine managers. This book is full of examples where properly used seismic data enabled solving production problems and increasing the underground safety standards. I want to believe that, when given the opportunity, mine seismology will return to the mines.

Phalaborwa, South Africa S.N. Glazer

Reference

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

Contents

Chapter 1
Introduction

Soon after I became a mine seismologist at Vaal Reefs Exploration and Mining Company Ltd., the analogue recording system was replaced by a digital one. This, together with the installation of more seismic stations, resulted in an increased number of recorded events. Something had to be done to manage this data. That's when I came up with the concept of apparent stress, and I then experimented with its various applications. One of the possibilities was seismic warning. This I presented to the owners of the seismic network. As a result, the managers of the Klerksdorp Mine Managers Association agreed to a test of the seismic-warning concept at No. 5 Shaft Vaal Reefs. These tests were successful because of the managers' active involvement. They supported this concept not only with millions of Rands but with their decision making that resulted in the positive participation of lower management. It appeared as if the mines had now developed and received a tool to improve underground safety. Still, despite massive capital expenditures on the installation of the seismic network, the concept was abandoned. Today I understand why. The management team that had supported the test departed due to the massive restructuring at Vaal Reefs Exploration and Mining Company.

This book is based on my Ph.D. thesis. Chapters 3, 4 and 5 are from that thesis. I had to make some slight changes, but these three book chapters are close to the original thesis chapters. My Ph.D. thesis is titled "Practical applications of stress index and other seismological parameters in combating rock-burst hazard in deep gold mine of Vaal Reefs, South Africa". Prof. A. Kijko was the advisor while Prof. S. Gibowicz and Prof. S. Lasocki were the reviewers. The thesis was submitted to the Department of Geophysics, Faculty of Geology Geophysics and Environmental Protection, AGH, University of Science and Technology, Krakow, Poland in June 1998. I am proud to present comments (i.e., excerpts) of my promoter and the reviewers:

1. From "An opinion of Mr. S.N. Glazer's Ph.D. thesis" dated Pretoria 28 January 1998 by Prof. Dr. Andrzej Kijko who was my Ph.D. advisor.

> "From my point of view, parts three and four are the most interesting ones. They constitute the detailed documentation of the author's opinion, development and evolution on the

S.N. Glazer, *Mine Seismology: Seismic Warning Concept*,
https://doi.org/10.1007/978-3-319-62353-5_1

> subjects of recording of mine induced seismicity and its interpretation methods. The described methods are the original ideas of the author. Very interesting are the applications, where the author describes with some detail, several cases of issuing seismic warnings before the occurrence of a strong ground motion seismic event and the reaction of the mining personnel. Very often the described problems are well beyond what are customarily discussed in papers or thesis"

2. From "Review of doctoral dissertation of Mr. Stefan Glazer, M. Eng. entitled Practical applications of stress index and other seismological parameters in combating rockburst hazard in deep gold mines of Vaal Reef, South Africa" dated 16 April 1998 by Prof. Dr. Stanisław Lasocki. Department. of Geophysics, Faculty of Geology, Geophysics and Environment Protection, University of Mining and Metallurgy, Cracow.

> "Employment at the mine has enabled Mr. Glazer to develop his own theoretical concepts and adapt those worked out by other teams regarding forecasting of rockbursts, and then testing them in the production conditions and to applying the research methods as routine methods for prediction and prevention. His doctoral dissertation presents this process from drawing up an inventory of observational data through working out methods and adopting the conception of prediction; consistent changes of observational methods: testing prediction methods in order to adopt—together with the management—the ways of their application in actual time, during production. Without diminishing the authors research effort, one would like to highlight the last aspect of that process—resulting both from the authors consistency and the openness of the mine management and supervision board to new ideas in the area of mining safety—the type of attitude which in Poland could only be hoped for"

3. From "Review of doctoral dissertation of Mr. Stefan Glazer, M. Eng. entitled Practical applications of stress index and other seismological parameters in combating rockburst hazard in deep gold mines of Vaal Reef, South Africa" dated 17 April 1998 by Prof. Dr. S.J. Gibowicz, Geophysics Institute, Polish Academy of Science, Warsaw.

> "The doctoral dissertation of Mr Stefan Glazer… is in fact a monograph which in a detailed manner describes the development of a seismic network, method of interpretation of seismological observations and their application to the mining practice of deep gold mines of Vaal Reefs in South Africa. I have read this dissertation with great interest and I am full of admiration for the author for his effort involved the collection and description of an enormous amount of seismological, geological, and mining data, as well as for his method of interpretation of seismic observations and their application in combating rockburst hazards".

Before settling in South Africa in 1988, I worked in England for eight years in the oil- and-gas exploration industry. When the price of crude Brent oil dropped to about 25 dollars a barrel, the exploration contracts ended. Then, as I remember, I thought to myself that the price of gold is good—at that time it was high and stable. So I decided that I should start working for the gold industry. That is how my adventure with mine seismology started. To be precise, my first contact with mine seismology was as early as 1964. At that time, studies started with a six-month practice in industry. As I was a student of AGH University of Science and Technology, Krakow, Poland, my work practice was in a coal mine. For these six months, my mentor was an old miner who was just about to retire. He has worked underground for his whole life and so did his father and grandfather. He did not have much education, but mines and mining he had in his blood. At the time, Polish coal mines were in the process of replacing the wooden supports with steel ones. The old miner did not like this. He told me that, when wood was singing, then you knew that it is safe. When wood was quiet then it was dangerous. The steel support had no voice and would deform with no warning. He had a good understanding of the rock mass. The rock mass had to release energy. If this process was continuous, then it was safe. On the other hand, the accumulation of energy in the rock mass coincides with the wood being quiet and implied danger.

I joined the gold industry as a mine seismologist at Vaal Reefs Exploration and Mining Company Ltd. I was lucky to join the South African Gold Mines when the mine management was still of the old school. At, heart they were farmers, and most of then still had farms. They even treated the mine as some kind of a farm. It is obvious that if you want to have good crop, then you must take care of animals, plants, and people. If someone was doing wrong, you had to shout at him only so he would know that he was in the wrong. That was nothing personal: it was a part of the education process. Lower-level managers were afraid of them, and never would contradict them. I have seen something similar to this in the Polish coal mines where I worked for eight years after graduating from the university. But it was different because the Polish communist mine manager was the king, and his position depended only on the tonnes mined. So there was no place for safety or diplomacy. The Polish mine managers were like tyrants and managed with a fist. The South African managers had a certain touch of nobility. I remember a joke about them. Two mine managers went to the club for lunch. After lunch, they decided to walk back so they send their chauffeur driven cars back to the mine. On the way, they saw a BMW car showroom, and one of the managers noticed a new model. He said “I don’t have one like this. I must get one”. He then takes out his cheque book. At this moment, the other manager says: “Wait now it is my turn, you just paid for the lunch”. At Vaal Reefs, I was in charge of the Klerksdorp Mine Manager Association (KMMA) Regional Seismic Network. This means that all working costs and capital were shared by Vaal Reefs, Buffelsfontein, and Hartebeestfontein Gold Mines and the fourth one at which underground operations came to an end in 1992, the Stilfontein Gold Mine. I had to present to the four (then three) managers the seismic budget. Usually I had two or three overheads always in the correct royal-blue colour. Any other colour would not be acceptable. When asked to enter and while approaching the managers, I heard that they were discussing cows and bees. After my short presentation, the chairman would say something in the line of “Thanks, Stefan. I assume that we have no problem with your budget”. This would mean that I could go. Before I managed to get to the door, they were again busy talking about cows and bees. This book describes my experience from 1988 to 2000 as a seismologist at Vaal Reefs gold mine.

Mining in Klerksdorp's district started as early as 1886. Deep level mining to depths of 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. Practical applications of analysis and interpretation of induced seismicity during the period 1970–1990 and its application to rock-mechanic recommendations are described in Glazer (2016). The later applications are described in my doctoral thesis (Glazer 1998). The advances made in the 1990s would not be possible without the fundamentals done in the past. One has to admit that the work done in the past was, and still is, of the highest quality. The methods of mining in the vicinity of seismically active geological discontinuities established in these years are still valid. Not much new has been added in recent years. Here I must add that seismically active faults and dykes are active because of mining. When I joined the Vaal Reefs Mine, I found out that death due to a seismic event is an "act of God" and that according to the top corporate management, the activity of geological discontinuities is due to nature. Only by chance did it happen that the gold was found close to these active faults, so one should not blame the mines for the seismic activity. By end of the 1980s, the network consisted of 29 geophone stations located in the vicinity of major production areas. Of those, eight were located on the surface. The underground geophones were located at depths between 400 and 2700 m. By 1982, it had been 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. One of the largest mining-induced seismic events recorded to date was at Vaal Reefs. It took place on 7 April 1977 and measured 5.2 on the Richter scale. It was associated with the fault that traverses the entire Vaal Reefs mining area. A second event of similar size took place in 2005. The third event of this size occurred in 2014.

Chapter 2, titled "Seismicity of the Klerksdorp Goldfields and the Resulting Seismic Hazard", describes the severity of the problem. Using the seismicity records for 1991, I estimated how the probability of a seismic-related accident changes during the day. To start with, I was stunned when I found out that during the day shift there were over 24,000 workers underground. This probability estimation, apart from considering the number of workers being at any time underground, made use of the 24-h distribution of seismic activity and of the seismic-energy release. The seismicity distribution clearly followed the mining cycle because, after the blasting, there was an increase in the seismic-activity rates. Seismic-energy release rates did not follow this pattern. Increases in seismic-energy release rates took place at different times of the day and the maximum occurred after 23:00. As a result, the probabilities of seismic-related accidents during the day were always there, with maximum values occurring between hours 9:00 and 12:00 and then after 23:00. I was in a position to verify the results because I had the accident data that included the times of the seismic-related fatalities. And, yes, my estimation of the 24-h distribution of the probability that some one will be killed in a seismic burst was correct. It did not make me proud but helped me to understand the severity of the problem I was faced with. During 1991, there were eight fatalities due to seismic events. A number of people were injured as the lost-time injuries due to seismic events during 1991 amounted to 121. At the time, the mine management made it clear that I am allowed to use statistics to probe the problem, but my findings must stay confidential and not to be published. By 1989, it was accepted that the Regional Seismic Network had the limitations associated with analogue-data transmission. In 1990, it was decided to upgrade the seismic-network facilities by installing the digital system known as the ISS (Integrated Seismic System). By mid-1990, the seismic system consisted of 30 geophone stations, of which 14 were located at Vaal Reefs. The introduction of the new system very quickly resulted in looking at the seismic events in a totally new way. The next three chapters are taken from my Ph.D. thesis. The changes that I had to make are minor as I wanted to keep to the facts and tried to present what I knew at that time.

Chapter 3 of the book is titled “Concept of Apparent Stress Index”. The content of this chapter is similar to Chap. 3 of my thesis which is titled “Role of applied mine seismology in the amelioration of rock-burst hazard (1990–1993)”. Both these chapters go back to 1990, that is, to the year when I defined the concept of apparent stress index. Before me, there were a number seismologist using data recorded by the Klerksdorp Seismic Regional Network, but they did not have the problem of too much data. Their problem was rather squeezing what they could from what was available. My problem was what to do with ever increasing amount of recorded data. It did not make sense to extend the network just to record more and more seismicity. It was essential to make use of this recorded seismicity. There was so much of it that it became impossible to scrutinise each event on its own. Even if this would be possible, then what would be the final conclusion? Would the statistical summary of all this recorded seismicity be the answer to what it was trying to present? At that time, I already knew and understood that the recorded seismicity had a story to disclose. It puzzled the mining personnel that underground damage did not always correlate with the event’s magnitude. The same magnitude event could result in severe damage or in no damage whatsoever. When the events were represented by their apparent stress values, it became clear that, for a given one value of magnitude, there is a wide range of apparent stress values. In this way very useful information was gained, and it quickly found practical applications. Areas of low and high apparent stress were established and the support strategy was then based on physical values. The next important application of seismic data came with the introduction of the concept of the apparent stress index at the end of 1990. This index was introduced in order to normalise events over a wide range of seismic-moment values. The index itself is calculated as the relationship between the measured and the mean values. This last is given by a regression line derived and based on all recorded events. In this way, index values above 1.0 indicate higher stress levels than average ones, while values below 1.0 indicate stress lower than average ones. Application of this concept was from the beginning clear, and the practical implications as far as the support requirements were straightforward. Contour mapping of this index resulted in optimization of support design. This concept was also used to compare various areas of the mine with each other, for example, it was used to compare seismicity for backfilled and conventionally mined areas. This resulted in a better understanding of the influence of large backfilled areas on seismicity. As a result, Vaal Reefs stopped using backfill. This decision saved the mine a great amount of money. During 1992 and 1993, the stress index concept was used to establish if underground working places are safe for re-entry after large-sized seismic-energy releases that resulted in fatal accidents. This type of data and analysis resulted in developing more involved concepts of using seismic data in the mines. At the beginning of 1993, the following conclusions were reached:

1. Large events are associated with areas where there are high gradients of the apparent stress index.
2. Damage can be experienced in areas where this parameter is high, even when the seismic event is located outside of these areas.
3. Before the occurrence of a major event, it would be possible to observe changes in the values of the index.

At that time, it was well understood that the above conclusions had practical implications from the rock-engineering and mining points of view. It was also obvious that the reliability and further application of the apparent stress concepts would depend on the network sensitivity and location accuracy. Testing the concept required an experimental seismic network designed especially for it application. Mine management had no problems with spending capital on this project. As a result, area 5B of No. 5 Shaft Vaal Reefs became a testing polygon. The eight-station seismic network installed during 1994 in this area became part of the Regional Seismic Network.

Book Chap. 4 is titled “No. 5 Shaft Experiment with Seismic Warnings”. This chapter in my Ph.D. thesis is titled “Management of seismicity at Vaal Reefs”. I decided to change the title but the content of the book and thesis chapter are the same. The experimental sub-network of eight stations at the 5B area became fully operational in September 1994. The first seismic warning was issued on 8 October 1994, and an event occurred in the expected area three days later. The test area covered by the experiment was 1.5 × 0.5 km in size (750,000 m^2). An average polygon for which a warning was given covered an area of 60,000 m^2 which represented 8% of the whole test area. From the seven warnings issued from the end of October to the end of December 1994, four ended in events of local magnitude above 2.5, and in two cases the underground working places were found to be too dangerous to continue to mine and as a result were abandoned. With one warning still in place, it became clear that a procedure for handling this type of information had to be formulated. Giving a seismic warning had at least two practical consequences. It indicated that a larger size event (or events) could be expected, but on the other hand, it also allowed for continuous monitoring of the situation. There might be ways of reversing the situation and enough time for taking some precautionary actions. As the introduction and use of the seismic warning concept in the 5B area was becoming practical from the seismic point of view, and the record showed that the method had credibility, some follow-up procedure had to be implemented. These procedures had to have two separate elements. The first was communicating the information, and the second involved the actions that had to be taken by those responsible for safety and mining. By February 1995 a procedure for handling seismic warnings was approved by mine management and put into practice. This procedure described preventive actions that had to be taken in all working places under seismic warning conditions. It also identified the person responsible for introducing them and described the control procedures. By the end of 1995, Vaal Reefs had already established a clear concept for a seismic monitoring strategy. This was a concept based on one central site, serving all Vaal Reefs shafts and mines and connecting all sub-networks and networks together. Consequently, the central site was rebuilt and equipped with new computer technology. A decision was made to increase the size of the seismic staff. From June 1994, the seismic central site was manned 24 h a day, on a three-shift basis. This resulted in improved processing quality of all recorded seismic events, but more importantly, all events of damaging potential were immediately reported to the shafts. This allowed them to send proto teams without delay straight to the affected areas. About that time, the Vaal Reefs Services Manager (second in command after the Regional Manager) took me to the Anglo American Head Offices in Johannesburg. Here we attended a presentation given by ISS International, a company that at that time was affiliated with Anglo American. When they presented the energy-index concept, Vaal Reefs' Services Manager could not take it any longer and announced "I and Stefan have been doing this already for years". It became dead quiet as no one dared to comment on the issue. To his satisfaction, it turned out (as it had always) that his farm was indeed better than any other one.

The experiment in the No. 5 Shaft 5B area lasted for 17 months. Those 17 months started at the end of December 1994 and ended in May 1996. During this time, we recorded 77 cases. The concept of seismic warning was successful 62 times, which was in 80% of cases. There were some false warnings after which nothing happened, as well as cases of missed events, which were not preceded by a warning. From the beginning of the experiment, Vaal Reefs adopted a philosophy that the success rate should rather be measured by preventive actions taken rather than by the success of a warning itself. Several preventive actions were put into practice that included additional safety pillars, changes in mining sequences and directions, and a review of the mining strategy for the whole area. Vaal Reefs' rock engineers, as well as the mine management, had no problem with the fact that seismic warning was limited only to indicating an area where, at some future time, a large-sized seismic event might take place. It was well understood that the timing and the event sizing are impossible to predict and that this is not even the ultimate goal of the experiment. There had to be and were cases in which a seismic warning turned out to be false. No one blamed the seismologists or had second thoughts about the accuracy of the concept. The following example illustrates the attitude at the mine. This example describes the follow-up procedure after a reason for issuing a seismic warning was detected in a polygon TRIBUTE2. At the time, this polygon included underground working places of mining section 56. It was found that all the panels in this section were mined in proper sequence and all of them had second escape routes in place and that they were clear. It was then decided to implement, with immediate effect, existing recommendations with regard to the use of two rows of hydraulic props with headboards in every working place. This recommendation, at that time, wasn't implemented due to a shortage of those props, but steps to overcome this problem became a priority. An underground inspection within the next couple of days was to take place to ensure that the recommended support was in place. The warning was then cancelled. The follow-up actions that were taken improved the underground safety standards and were therefore not a wasted effort from the point of view of the mining personnel. The experimental seismic network was used for more than just issuing seismic warnings.

The first example involves blast-timing and mining-strategy changes for working places located along the Vos Dyke. Dykes in the 5B area were known for their seismic activities, and the Clemcor Dyke was called the "Killer Dyke". During May of 1995, a warning was issued for a workplace, located close to the Vos Dyke. After eleven days, two large-sized events occurred within 12 min of each other. Two days later in the same area, two people were killed due to a rock burst from the Vos Dyke, which was much closer to the face than the plans indicated. This rock burst resulted from blasting the panels located along the Vos Dyke at a different shaft, away from the place of the accident. In June 1995 a seismic warning was given for an area also located along the Vos Dyke. As a result the panel was stopped and drilling indicated that the dyke was much closer to the face than expected. Probably because of this the mining in that place was then stopped permanently and the event did not take place. This is an example of an extremely successful warning, in spite of the fact that it was not followed by a seismic event. In this working place, located to close to the dyke, seismic event could have injured or killed people, as the recorded seismicity indicated that the dyke was highly stressed. Based on this type of information, it was decided to scrutinise blasting times for mining areas in the vicinity of the Vos Dyke. At that stage, that time varied from 14:10 in the 2K area of No. 2 Shaft to 16:10 in the 5B area at No. 5 Shaft. In order to minimize the risk it was then recommended that the earliest blast time be 15:20 for all production sections. This recommendation was then put into practice, and to date (May 1997) there were no fatal accidents associated with the Vos Dyke. It was also decided to minimise the number of working places that were located along the same seismically active fault or dyke. The other example is connected with analysis of seismicity at No. 5 Shaft for the period February 1995 to July 1995. It was noted that there was a significant change in the pattern of seismicity in July, in comparison to the time period from February to June. It was then concluded that that the then-present method of mining is locking up the faults and dykes, not allowing the release of energy in a continuous manner. Safety and bracket pillars were designed, and, in general, mining towards dykes was stopped. Mining directions were changed to run along the dykes. In order to decide the pillar sizes (between the working places and the dyke), intensive drilling works were started immediately.

These two actions that resulted in increased underground safety were due to the fact that the area had good seismic cover and that the mine's professionals were making use of the recorded data. These examples indicate that it will be never possible to achieve such results by analysing only seismic data at a remote place from the mine. The No. 5 Shaft experiment was a success because it was supported in an active way by the mining and rock-engineering personnel. Despite the fact that the seismic warning concept at the time was not a fully reliable management tool, its potential for underground-safety improvement was recognized by management. This then resulted in the implementation of this concept over the entire Vaal Reefs mining area. It was a costly decision regarding capital expenditure and running costs.

At the end of this chapter are listed conclusions based of the 5B experiment. One of the observations about the size of events for which there was a warning was that the success rate decreased with size. For events above magnitude size $M_L = 3.5$, there were no successes. Heunis (1977) made an observation that faults of large displacements (40 m+) present special rock-burst and rock-fall difficulties, because the risk of very large seismic event is considerably amplified by their presence. Little is known about the methods of preventing the occurrence of these very large events. According to Gay et al. (1984) there is a very good correlation between the number of events and the total area mined. From the plots of cumulated energy released by seismic events against centares mined, a very interesting conclusion was made. It is that the occurrence of big events seems to be independent of the mining activity. Johnston (1992), after a comprehensive study of mining-induced seismic events in various parts of the world, divided them into two categories. The first category includes events of low- to medium-sized magnitudes, whose event rate is, in general, a function of mining activity. They are located generally within 100 m of the mining faces on a geological discontinuity. Events of the second category are events of high magnitude, are difficult to correlate with mining, and occur on pre-stressed faults. These events are then, in some undefined way, triggered by mining activity. On 10 February 1997, a large event of $M_L = 4.3$ took place very close to the experimental area of 5B at No. 5 Shaft Vaal Reefs (Glazer 1997). At the time, there was no warning given, as all monitored polygons did not indicate any reason to issue a seismic warning. This event was located on the No. 5 Shaft Fault, which has a displacement of more than 100 m. The main shock was then followed by a number of aftershocks that were located on the fault itself and on the intersecting dykes. The size of those aftershocks was between $M_L = 2.0$ and $M_L = 2.7$. There were in total 20 of them, and they occurred from 10 to 15 February. There were no events recorded in close proximity of the source of this event prior to its taking place. The only one was the $M_L = 4.3$ event that took place six years earlier on 1 January 1991. From this, it was concluded that the mining-induced seismic events at Vaal Reefs follows a triple-mode distribution, rather than the bimodal one, and that those events can be divided as follows:

1. After-blast events that are due to fracturing in front of the faces (small events up to $M_L = 0.5$).
2. Events connected with local small- to medium-sized faults and dykes. Those events can be up to magnitude $M_L = 3.0$ and are associated with present mining.
3. Events above $M_L = 3.5$ that are associated with regional structures. These events are associated with the whole history of mining in the area.

Some of the 5B post-experiment conclusions were as follows:

1. My original concept of apparent stress index, which was formulated at the end of 1990, proved to be very useful for seismic-data interpretation purposes and has found several practical applications.
2. The application of the instability concept at the experimental area of No. 5 Shaft Vaal Reefs was a success, not only from a seismological point of view, but, what is more important, it resulted in increased safety in underground working places.
3. In view of all the listed limitations, this success might be difficult to understand. It is possible that the concept itself is so straightforward that it does not depend strongly on the quality of the input data. It is also possible that, by chance, the sub-network configuration was optimal and, because of that, it acted as a data filter.
4. A seismic warning is limited to indicating an area that might experience a seismic event and is not time specific, and it cannot indicate the size of the future event.
5. Despite the fact that the application of the stress index concept was not a fully reliable management tool for combating rock-burst hazard, its potential for improving underground safety was at the time well recognised by mine management. Proof of this was its implementation over the whole of the Klerksdorp mining area, where the number of operational seismic stations increased from 32 in 1990 to 97 in June 1997, with more yet in various stages of installation.

Chapter 5 is titled “Status of the Networks in the Klerksdorp Area by June 1997” while the thesis Chap. 5 is titled “Present status of seismic networks in the Klerksdorp area by June 1997”. Both describe in greater technical detail the Klerksdorp Regional Seismic Network, its sub-networks, and the Vaal Reefs seismic networks, which came on line during 1995–1997. The Regional Seismic Network served all three mines of the area, providing general seismic cover. From a typical regional network, as it was in 1990 with about 30 recording stations, it evolved into a hybrid network. This was first intended to test the warning concept at the 5B area of No. 5 Shaft Vaal Reefs. After the concept proved to be of practical use in the mine, other sub-networks joined in, this time to introduce the concept to other areas in the most economical way, that is, by making use of existing central site facilities. When it became technically impossible to add new sub-networks to the regional network, several independent networks were put into place. The sub-networks were:

- 5B area of No. 5 Shaft
- No. 1 Shaft Vaal Reefs
- No. 2 Shaft Hartebeestfontein
- No. 4 Shaft Hartebeestfontein

At that time, the 5B sub-network was extended to the 5D and 5E areas with the installation of new underground stations. In total, at that time, there were 130 recording stations. By mid-1997, there were 15 staff members employed by the seismic section. They were divided into three groups, each performing specific tasks that interlinked with each other in order to produce high-quality output information. In order to inform each staff member of problems and progress, every day started with a short, informal meeting. Additionally, all reports were circulated for everyone's information. The three groups were: technical, computing, and seismological sub-sections. That is where the fun ended. Managing this group of people and managing at the same time a number of capital projects (all connected with new networks) slowly transformed me from seismologist to administrator. It is unfortunate that often a successful professional carrier ends when management wants to show it gratitude and to provide a higher salary. This is then connected with promotion to the ranks of management. A professional specialist, at least at that time, could not have a higher salary than the managing official. The result is meetings, then more meetings, budgets, financial reports, and as a result less and less contact with mine seismology. But I was lucky. The Vaal Reefs General Manager had me on his list to discuss my future with the mine. Such meetings were nothing out of the ordinary. It was a routine that the General Manager personally spoke with each employee above a certain managerial level. This was not my first personal contact with the General Manager. We met at least twice a year for the KMMA Regional Seismic Network and then for the annual dinner. The latter was probably the grandest social event in Klerksdorp. It was important to be invited as this put you into the top social rank. All the women carefully prepared their outfits, and everybody was talking only about this event. The Regional Manager and his wife greeted everyone at the door; the tables were full of food and wine. A speech was given by the GM, after which there was some cabaret or other artistic performance, followed by dinner and dancing.

My other meetings with the GM were totally different. I remember that it was 1 April but do not know which year it was when I got a telephone call apparently from the GM's secretary. She told me that the GM was to host a Russian delegation, and he wanted me to help out and then stay for lunch. I just thought "Aprils fool", took out my sandwich, and forgot all about it. A couple of days later I got a phone call, this time from the man himself. He introduced himself and then asked if I knew who was on the second end of the line. Then I was told that he expected me to help with the Russians, describing their eating and drinking habits, and I was to attend the dinner. I was probably the only person in the entire 40+-year history of the mine who did not attend a lunch for which a GM had sent an invitation. I also had my minute of fame. I made sure that there was vodka in the deep fridge and organised proper glass hardware for its drinking. Dinner turned out to be a success, and the

Russians started toasting. Some of the toasts where quite long and were about the Russian miners respect for the South African ones. During a break, the GM asked me to make a toast. I then put together my whole knowledge of the Russian language and came out with “To the women” (in Russian). I received applause and a long ovation from the Russian delegation. I saw amazement on the GM face, but he did not ask me for translation. Going back to the meeting about my future, I made it clear that I am very unhappy in the managerial position and that I would like to be back doing mine seismology. We then decided that for my future it would be beneficial to do a doctorate. The mine would pay all costs. Additionally I received a 15% salary increase. I practically started to write my thesis the very next day and during office hours.

The concluding Chap. 6 is titled “What Happened after 1997?” Up to this point, everything indicated that life must add a happy ending to this story. One would imagine that the concept of seismic warning based on apparent stress index (or energy index) would become a permanent seismic/rock engineering tool used not only for combating seismic hazard. But it did not happen, as I see it today, for a number of reasons. In 1998, ARM (African Rainbow Mining) was formed and took over from AngloGold shafts at which there were dense and modern networks. The KMMA Seismic Liaison Committee became the Seismic Network Management Committee. The ARM mine became the biggest contributor to the working costs of the seismic central side. The main purpose of the network was now only to supply quality seismic databases and continue with the 24-h monitoring and recording. The contacts between me and the mine seismologists became very irregular. The mine seismologists were now part of the mine’s rock-engineering sections and reported directly to the Rock Engineering Manager. In addition, there were numerous problems with the new version of software that was installed by the end of 1996. Those problems carried on for the next 12–14 months. Due to this, the seismic warning method wasn’t practically used for the whole of 1997. All interpretations were of low quality and Rock Engineering personnel lost confidence in mine seismology. Because of the new Health and Safety Act, the Rock Engineering staff concentrated a lot of their efforts on legal aspects, as well as on preparing the Code of Practice. By the end of 1997, new software was installed and a time-and-effort-consuming process for recalculation of all the databases had started (as far back as 1990). This task was finally completed by the end of 1999. By this time, the KMMA Regional Seismic Network ceased to exist. By the end of 1999, AngloGold decided to pull out, and as a result, at the beginning of the year 2000, each mine operated its own separate network. As the Shafts (now mines) did not have the knowledge and personnel to run the seismic networks, its management was outsourced to contractors. In the end, there was only one contractor left (the ISS) who was contracted to do all the work, starting with processing and providing seismic-data interpretation and seismic reports. In this way, all seismic-data analysis and interpretation were eliminated at the mine. In addition, this contractor pushed with its own concept for seismic-alert alarm and scram.

This chapter was not part of my thesis. The first version of it I wrote during 2000. At that time, I was doing some work for CSIR on a Safety in Mines Research

Advisory Committee (SIMRAC) Report GAP 608 “Survey and Assessment of Techniques Used to Quantify Potential for Rock Mass Instability” (Brink et al. 2000). Here my contribution was the part titled “Seismic warnings as used in areas where seismicity is driven by geological structures.” My observations about the failure of the seismic warning concept were not included in this report. I have rewritten this chapter for this book. In the last decade of the last century, a lot of confusion has arisen as to what is a seismic warning. Is it some kind of prediction, which then can be graded in terms of alert, alarm, and scram, just as in the case of military warning systems? Press and some false public statements in regard to advances in seismic research did not help in resolving this matter. When the seismic warning concept was introduced, the mining personnel and the seismologist, as well as the Rock Engineering personnel, were very enthusiastic about its potential. The general feeling was that at last there is a proactive method that can help to improve underground workers’ safety. Then, with the introduction of the Health and Safety Act, this perception changed. The problems that arose were the legal responsibility and the transparency problem. The important issue was would the workers exercise their right to refuse to work in dangerous areas. The dangerous areas would then be the locations where a seismic warning was in place. The next problem would be how this would affect the mine’s production. It is my opinion that this was an imaginary problem. All around the world, people work in dangerous situations and accept it as normal, often forgetting the danger. I personally had this experience while working underground at a mine that was known for a number of fatalities due to poisoning from carbon monoxide. This gas was concentrated in high-pressure pockets in some of the faults. For this reason, all underground personnel had to carry oxygen apparatus. Some dead miners were found in position indicating that they were trying to use the mask but only after they had inhaled the gas. My work at that mine was to try and find the fault position using a seismic-reflection method. The shot points were in boreholes drilled into the rock. After a short time, the oxygen canister becomes very heavy so I have hung it somewhere in the area of work. The warning system from its beginning was there to remind underground personnel of the realities and to put them on guard. According to Northwest Record of 20–21 January 2000, the team leader of the group of 15 mineworkers who were trapped underground for more than 80 h after the seismic event stated that: “he will definitely go underground again since he has a family to look after”. At that time the Rock Engineering personnel would rather recognise the seismic warning method only as a research project until it would be able to provide the accurate time, location, and size of future events. As this was an impossible request then, the seismic warning system was eliminated from the mines. It might be interesting to look a bit closer at the bigger picture of what was happening at the time. From 1944 up to 1998, Vaal Reefs Exploration and Mining Company Ltd. was growing continuously and became one of the world’s largest gold producers. AngloGold Ltd. was formed in June 1998 through the consolidation of the gold interests of Anglo American Corporation of South Africa Ltd. (AAC) and its associated companies.

This is the big picture as seen by the top AngloGold corporate management. The story as seen from the lowest level was very different. First there were rumours that there might be some changes, and then the name of the game was management of the changes. There was an outside company doing an audit that involved all employed people. We had to fill in questionnaires and describe our jobs. A lot made up their job descriptions in order to make them more important. As a result, the audit appeared to show that many work positions were performed in duplicate or even triplicate. This implied that there was too many employees and not enough work for them all. Additionally, the entire personnel of the Rock Engineering Department, including the Seismic Section, were interviewed by the mine's seismic contractor. This was official, and the interviews were conducted in the Regional Rock Engineering Manager office with the manager absent. We were instructed to provide all information required. I remember that during this interview I was reprimanded for the high working costs. Apparently our costs per recorded seismic event were too high. By the way, part of my working costs was hardware and software maintenance which was paid to this contractor. During all the years when I worked for the Vaal Reefs Mine, I was never treated in this way by a mine manager. This fact was a clear indication to the Rock Engineers of what they could expect in the near future. As expected, the draft version of "A Guide to routine seismic monitoring in mines" (Mendecki et al. 1998) was made accessible to the industry by the end of 1998. The first comment I received about this guide, even before I had read it, was "that the industry allowed to give the task of preparing such a document to the same people who research, produce and sell seismic equipment and software" With some changes, this guide was based on the book "Seismic Monitoring in Mines" (Mendecki 1997). In the preface to this book, the editor lists the three objectives of seismic monitoring in mines, namely:

- To verify the parameters and assumptions of mine design while mining
- To predict larger instabilities
- To back-analyse, so that we learn from history

In the guide there are five objectives:

- Location of potential rock bursts
- Prevention
- Control
- Warnings
- Back-analysis

So it was not a surprise that the Code of Practice Research and Development Considerations started with the following sentence: "Rock-burst control on AngloGold Ltd., Vaal River Operations, is based on the ultimate concept of: ALERT, ALARM AND SCRAM."

I stayed with the mine until the end of 2000, that is, until I was released. For the next couple of months, I tried to find a job in mine seismology, but no one could afford to employ a highly educated specialist. It turned out that I was overeducated for any job in my profession. So I decided to take advantage of the 'Dr.' in front of my name and started to give private lessons in maths and science. The title of doctor allowed me to charge more than the others in this business, and it probably gave the parents false confidence that their children were in good hands. My private school closed in February 2002. I got myself employed by Palabora Mining Company located in Phalaborwa. And, yes, by the year 2000 the price of gold was much lower than it was when I had started in the gold-mining industry. My adventure with the copper industry lasted until the end of 2013, when the new owners could not afford to pay for my services and experience. My experience with copper mining is described in my first book Glazer (2016) titled "Mine Seismology: Data Analysis and Interpretation" . There is a saying that you can not swim twice in the same river. Well, the mining industry proved that this is not always the case. When I arrived at the mine in 2002, the seismic system was partially operational, i.e., it was already recording some of the induced seismicity. A female geologist was in charge. At that time, mining in the open pit and developing of the underground mine were two operations that could not be performed at the same time. Before every blast, the underground site had to be evacuated. This usually was a complicated and time-consuming operation because a blast was not allowed until the last soul had been accounted for. The mine had to pay the contractors penalties for keeping them out of work. I then analysed the recorded ground-motion amplitudes and decided that it is safe to blast in the open pit and keep the underground operation going at the same time. My report was based on seismicity that was recorded before I started to work at the mine. The data was there, but the person in charge of the seismic network did not know about this. When I left the mine, I left behind a person in the position of seismic technician. This person has no formal qualifications for the job but, with time, gained experience. He was and is a first class processor and can take care of the networks hardware. He knows nothing about seismology. By mid-2016, I was told that again a female geologist is in charge of the seismic network and that the seismic processor was given the task of training her in mine seismology.

Finally I need to make three comments. The first one is in regard to the figures that are in this book. All of then (that is, the originals) I made while writing my thesis during 1997. When I decided to write this book, I acknowledged that there is a problem with the quality of these figures. All figures are from the thesis. I have no data or software to reproduce them. I had to redo them and I have copied them by hand. For this reason, there are some differences between them and the originals. Those differences are not important, as all my interpretations were based on trends, and the absolute values were of no importance. The second matter is terminology. At the time (1990–1997), the terminology used was not as important as the results achieved. And the results were measured in underground-safety standards. This underground environment was the subject of high-seismic hazard, for which the proof was the number of fatalities and injures due to seismicity. So no one, starting with me, the rock engineer, or the mine manager was too worried if what we were doing is 'seismic warning', or some kind of prediction, or what are 'instability' and any other similar terminological phrases.

The third comment is connected with so-called out-of-place artefacts, a name given by pseudo-scientists for historical and archaeological facts they believe could not have been created by a particular culture due to a lack of knowledge or materials. In other words, they have been created by some outer-space civilisations that for some reason had visited Earth. In the Klerksdorp Museum, I have seen the "famous" Klerksdorp Spheres. These spheres were found in nearly three-billion-year-old mined deposits near Klerksdorp in South Africa. Much of the pseudoscientific explanations are based on the false claims that the objects are perfectly spherical, are made of a metal or alloy of unusual hardness, and are so finely balanced that modern manufacturing processes could not replicate them. There are claims that National Aeronautics and Space Administration (NASA) found the spheres to be so precisely balanced that they concluded that they could not have been constructed on Earth, but would have required a zero-gravity environment. There are also reports that the spheres can vibrate because they contain some internal energy. Because of this, they are able to change their locations with no outside intervention. And there is a group of people that believe and insist that this is a fact. Here comes the science of seismology that explains the reason for the spheres changing their locations. The museum, as does the whole town of Klerksdorp, experiences vibrations due to mining-induced seismicity. The spheres move due to strong ground motions. This proves that seismology also can be used as a tool to oppose pseudo-scientific theories.

References

Brink AvZ, Hagan TO, Spottiswoode SM, Malan DF with external contributions from Glazer SN, Lasocki S (2000) SIMRAC Project GAP 608 survey and assessment of techniques used to quantify the potential for rock mass instability SIMRAC website: www.simrac.co.za

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. In: Symposium of South African Institute of Mining and Metal, Ser. No. 6. Johannesburg, pp 107–120

Glazer SN (1997) Applied mine seismology: a Vaal Reefs perspective. In: Gibowicz SJ, Lasocki S (eds) Proceedings of the 4th international symposium on rockburst and seismicity in mines. Kraków, Poland 11–14 Aug 1997, Balkema, pp 227–231

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, Kraków, Poland, June 1998 (in English)

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

Heunis R (1977) A report on the interim conclusions of the rock burst project (1973–1977) rock burst Project Report No. RP. 37. Chamber of Mines of South Africa, Johannesburg

Johnston JC (1992) Rocburst from a global perspective. In: Knoll P (ed) Induced seismicity. Balkema, Rotterdam, pp 63–78

Mendecki AJ (ed) (1997) Seismic monitoring in mines. Chapman and Hall, London

Mendecki AJ, van Aswegen G, Mountfort P (1998) A guide to routine monitoring in mines. In: Jager AJ, Ryder JA (eds) A handbook on rock engineering practice for tabular hard rock mines. Creda Communications, Cape Town, 1999, on behalf of the Safety in Mines Research Advisory Committee to the Department of Minerals and Energy of South Africa

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).

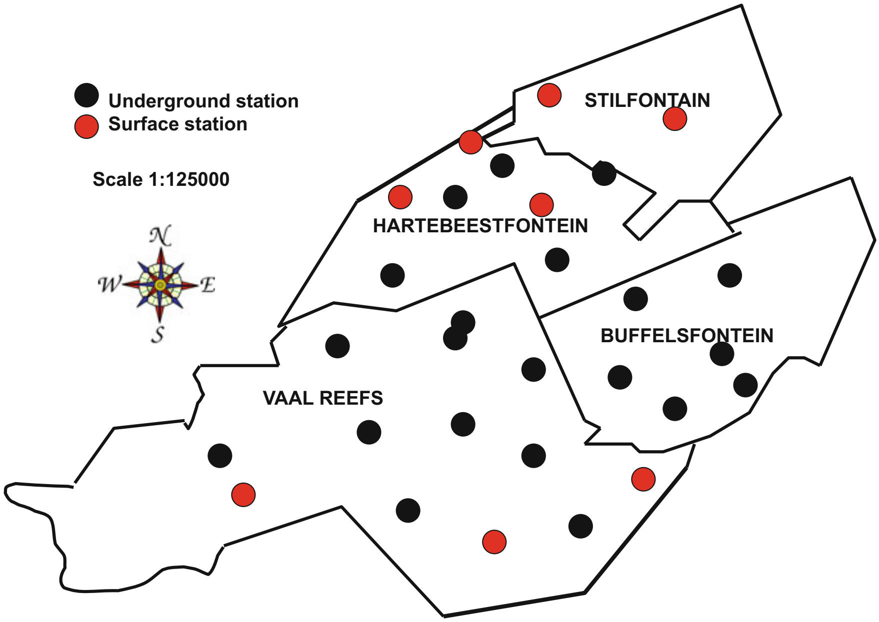


Fig. 2.2 Klerksdorp Regional Seismic Network, 1988

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:

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

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

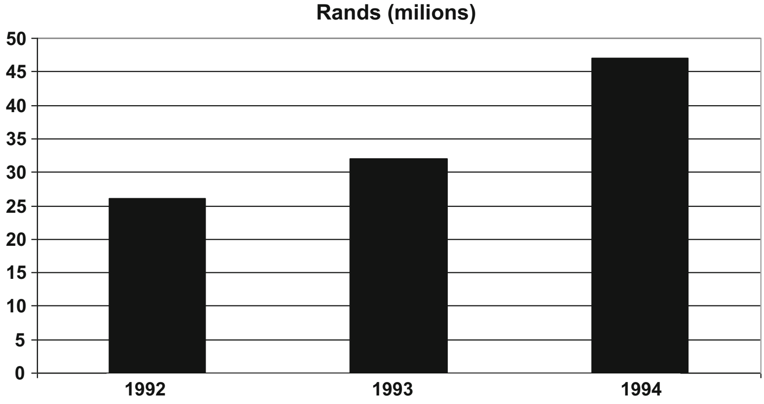


Fig. 2.3 Total cost of lost production for Vaal Reefs

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.

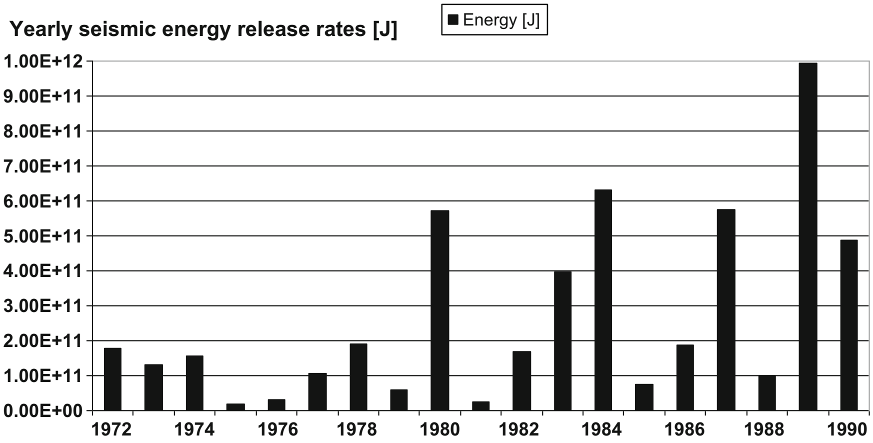


Fig. 2.4 Yearly seismic energy release rates

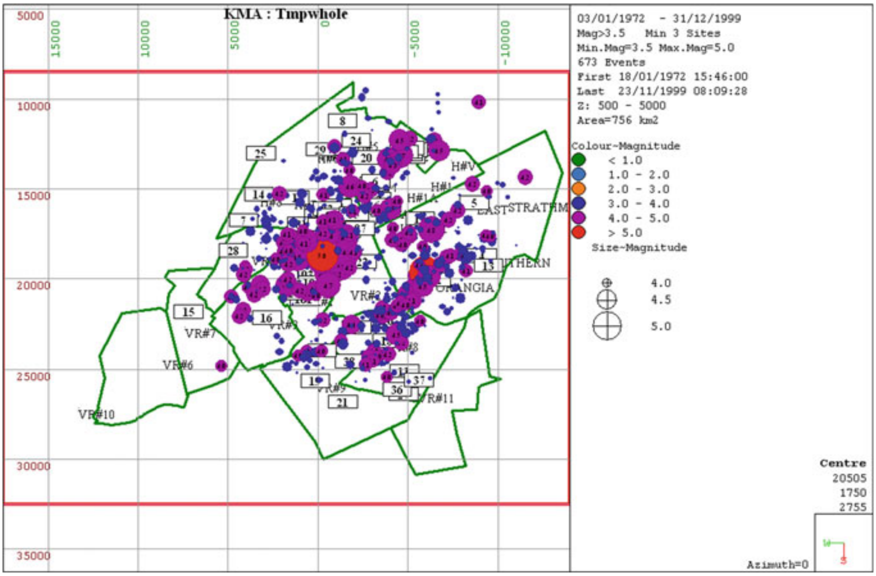


Fig. 2.5 Seismicity of magnitude 3.5 and above

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).

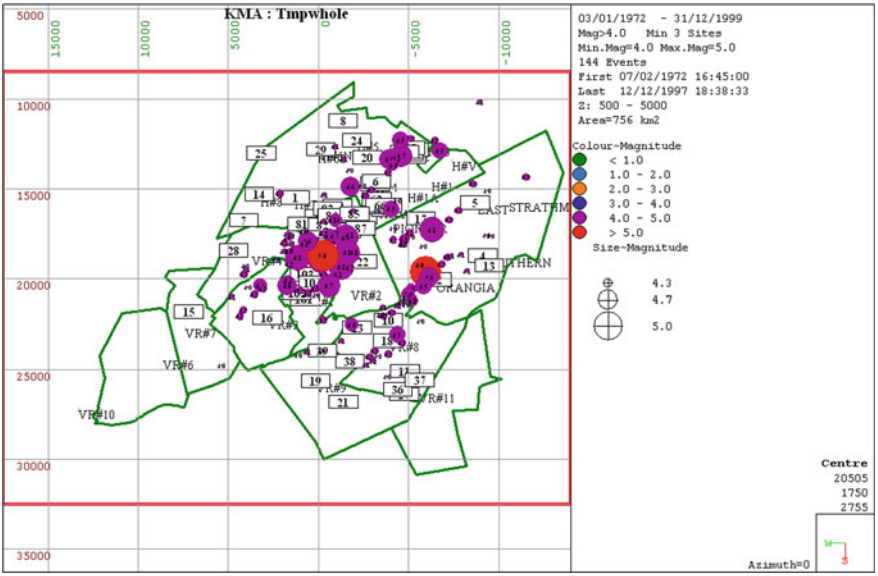


Fig. 2.6 Seismicity of magnitude 3.5 and above

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

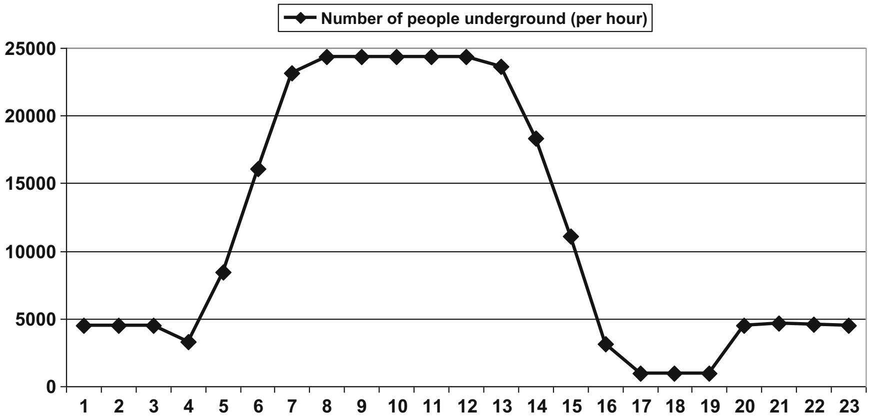


Fig. 2.7 Number of underground workers per hour at Vaal Reefs

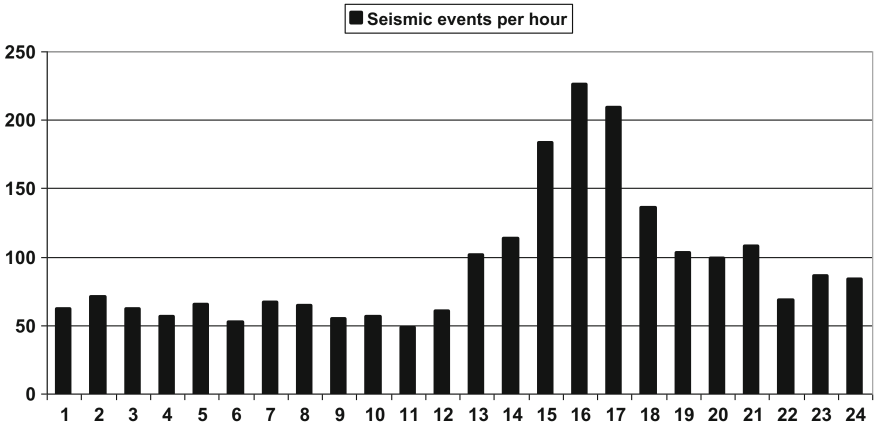


Fig. 2.8 24-h distribution of seismicity

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

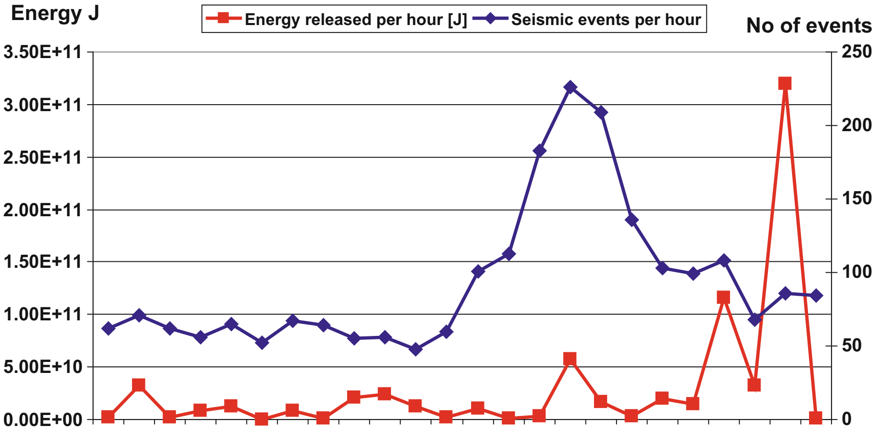


Fig. 2.9 24 h distribution of seismic energy and number of events

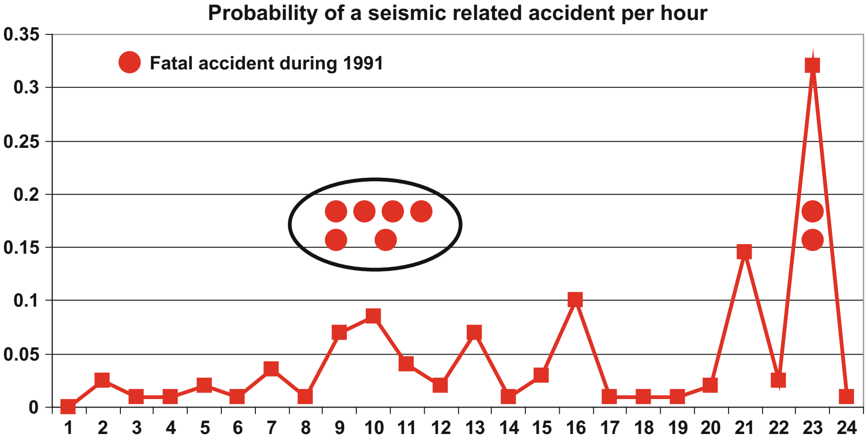


Fig. 2.10 Probabilities of seismic related accident

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.

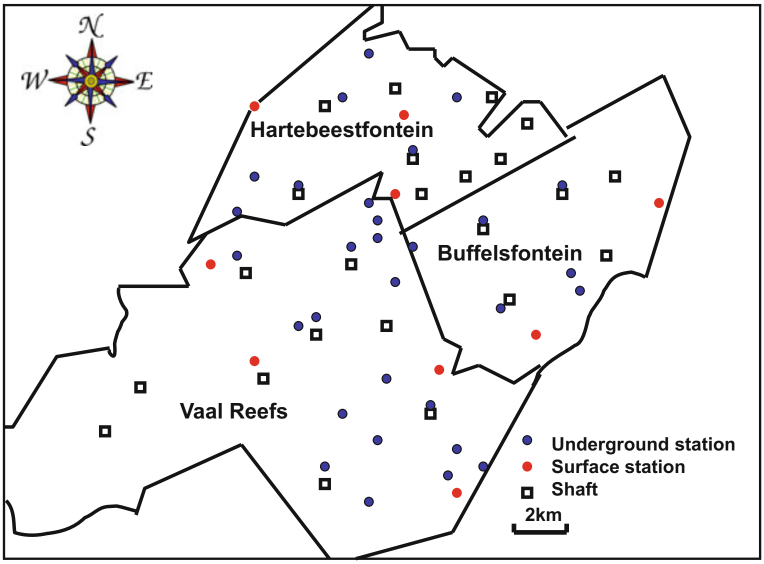


Fig. 2.12 KMMA Regional Seismic Network configuration by the end of 1993

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

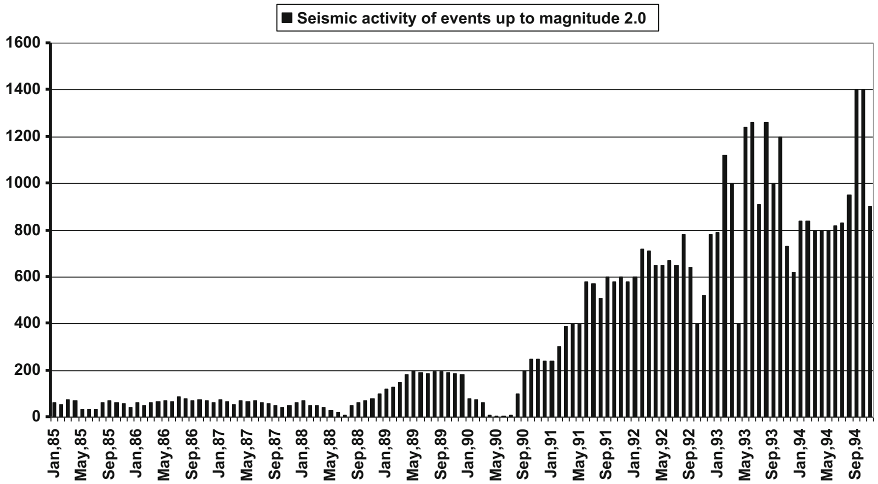


Fig. 2.13 Monthly seismicity (up to $M_L = 2.0$) rates between 1985 and 1993

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

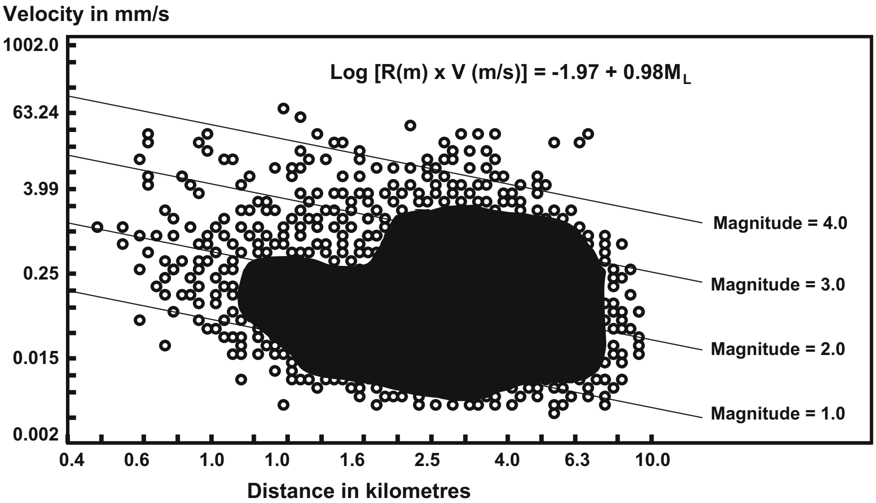


Fig. 2.14 Distance versus maximum ground motions (1991)

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:

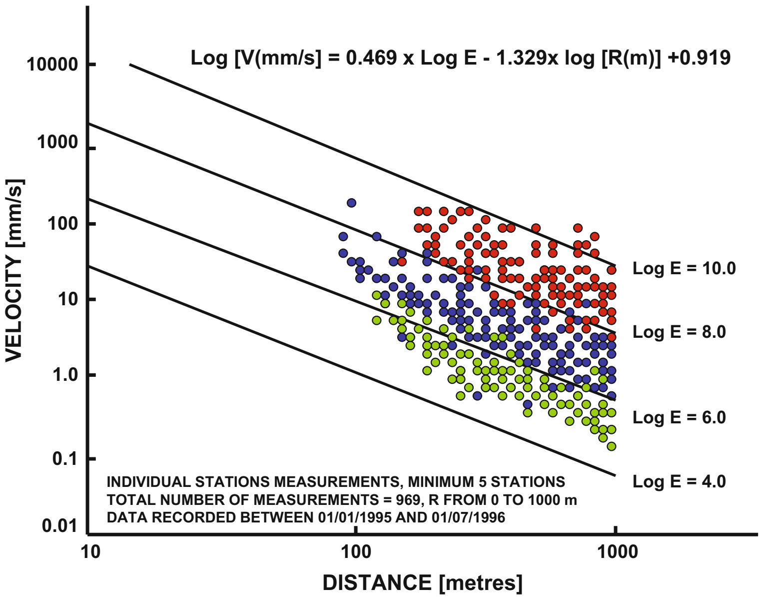


Fig. 2.15 Distance versus maximum amplitude of ground motions (1996)

$$M_L = 0.333\log(M) + 0.263\log(E) - 3.613$$
$$\text{and finally: } \mathrm{Log}(E) = (M_L + 1.192)/0.478$$

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

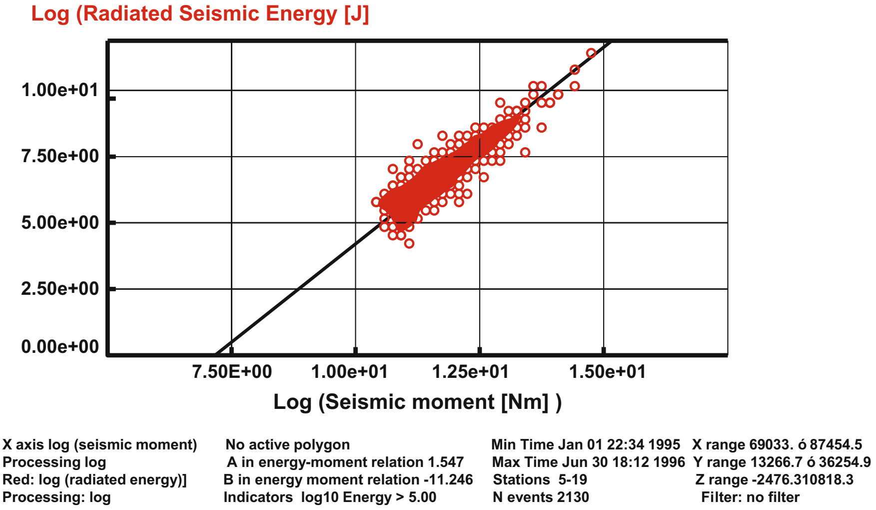


Fig. 2.16 Energy-moment relation for events above 1.0

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

Chapter 3
Concept of Apparent Stress Index

In this chapter, I describe the idea behind the apparent stress concept. It was developed in order to cope with increasing amounts of recorded seismicity. My thinking was that, if the recorded seismicity cannot be used in the process of data analysis and interpretation, then there is no reason to record more and more. Having developed the index, the next step was to sort out the methods for using it for practical purposes. Hence ensued my test of plotting its contour plots or presenting the index in the form of time histories. The other important conclusion from the tests was that the really small-sized events are providing valid information about the rock-mass stress condition. All presented tests were done with seismicity recorded by a regional network. In case of a regional network such as the size of the one at Klersksdorp, the distances between the recording stations were measured in kilometres, and the seismic catalogue was complete, perhaps, from a magnitude size 1.0. If the developed methodology was to be tested rigorously, then the input data should consist of hundreds or thousands of events of very small-sized seismicity. For this reason, it was decided to install an experimental seismic network at No. 5 Shaft Vaal Reefs. Now, it is easy to say it was decided, but this installation required not only capital and a lot of man-power hours from the shaft itself. For this, the management had to be convinced that they would get something in return. Getting management's positive decision was not difficult because they were well informed of all developments and experiments with the recorded data, such as those that were being done at the mine. I was also presenting the actual state of experimentation at meetings of several mine managers on regular basis.

By mid-1990, the seismic system consisted of 30 geophone stations of which 14 were located at Vaal Reefs. The introduction of the new system resulted in viewing the seismic events in a new way. The best example illustrating this is the introduction of the apparent stress concept into practice. It has puzzled mining personnel that underground damage did not always correlate with the magnitude size of a seismic event. The same magnitude event could result in severe damage or in no damage whatsoever. When the events were represented by their apparent stress values, it became clear that one range of magnitude was represented by a wide

S.N. Glazer, *Mine Seismology: Seismic Warning Concept*,
https://doi.org/10.1007/978-3-319-62353-5_3

range of this value. As a result, useful information was gained, which led to practical applications. Areas of low and high stress levels were established and a support strategy could now be based on measured physical values. Another practical rock-engineering application of seismic data was the use of the locally recorded, peak ground velocities in calculations of the support resistance. The concept of apparent stress index and its application for evaluation of seismic hazard originated at Vaal Reefs at the end of 1990. It was my concept. At that time, we were not allowed to publish, and we were not expected to attend conferences or seminars even when they were taking place in South Africa. My concept was then used with modifications at the Welkom Seismological Network (van Aswegen and Butler 1993; Mendecki 1993) and at the seismic networks of the Western Deep Level (WDL) mines (Butler 1997). In Welkom, it became known as the energy index, while at WDL as the weighted energy index. The original concept was derived from the definition of the apparent stress itself. Apparent stress is based on the estimation of radiated seismic energy and seismic moment (Snoke et al. 1983; Wyss and Brune 1968)

$$\sigma_a = \mu E/M\mathbf{o} = \eta\sigma$$

where

μ	Shear modulus
E	Radiated seismic energy
η	Seismic efficiency
$\sigma = (\sigma_1 + \sigma_2)/2$	Average stress acting on the fault
σ_1	Stress level before the event
σ_2	Stress level after the event.

Snoke (1987) proved that if the P-wave contribution to the seismic energy and the azimuthal dependence of the energy are neglected, then $\sigma_B = 2\sigma_a$. The Brune stress drop σ_B is strongly dependent on the assumed model. On the other hand, if the contribution of the P-wave energy is taken into account in the energy-release calculation, then the apparent stress becomes an independent energy-release parameter (Gibowicz et al. 1990, 1991). As the value of apparent stress is proportional to the shear stress acting on the fault, it then appears that higher apparent stress might indicate higher shear stress acting on the fault, while lower apparent stress should then indicate lower shear stress on the fault. Because of this relation, it was assumed, at the time, that it has a potential to be used for mapping areas of higher and lower stresses. The upgraded system used by the Klerksdorp Regional Seismic Network provided, among other parameters, the value of apparent stress for every processed seismic event. The value of apparent stress is calculated independently of the magnitude, as the latter is calculated from moment and energy, which means that events of the same magnitude can have different values of apparent stresses. From this, it was then concluded that even the smallest events carry useful information. There is a relationship between the magnitude and apparent stress values.

Table 3.1 Relation between local magnitude and apparent stress

M_L ±0.2	Number of events	Mean value of σ_a (Pa)
1.0	307	3.4E+04
1.3	239	6.7E+04
1.5	430	8.9E+04
1.7	413	1.3E+05
2.0	322	2.0E+05
2.3	253	3.3E+05
2.5	219	4.7E+05
2.7	160	6.6E+05

The larger the magnitude, the higher in general is the apparent stress value (Gibowicz and Kijko 1994). This fact was confirmed using data recorded at the Klerksdorp Network. By the end of 1990, on the basis of a limited number of recorded events, the following relationship between M_L and values of apparent stresses was established. Table 3.1 presents this data for the Klerksdorp Mining area as it was estimated during 1990.

This relationship between apparent stress and magnitude reduces the application of apparent stress as such for interpretation purposes to events of the same magnitude. Still, if there are two events of the same magnitude but of different apparent stress values, then such observation enables assumptions about the stress distribution. In order to make use of all recorded seismicity, a new approach was necessary. So the concept of apparent stress index was introduced. In order to calculate the apparent stress index, one has to know two values: the measured and the mean value. The mean is presented in Table 3.1, while the measured one is the value of apparent stress calculated for every event. The first application of this index was to use its values to produce contour maps. At the time, it was assumed that, because of the limited amount of data in the database (May–December 1990), the mean value will not be accurate. However, for the purposes of formulating the concept, it did not matter. If proven correct, with time this limitation would then become unimportant. It was then assumed that there are other limitations that are more important. The first one is that the concept will only be valid for those parts of the mine that have already experienced seismic events. It will not apply to those parts of the rock mass that do not experience seismic events and will also not apply to those areas that are outside the seismic cover. Again, if the concept would be proven correct, time will work in its favour because, with network development, more and more ground could be covered in the future. The second limitation was the location accuracy. The regional network had, at the time, reasonable location accuracy, but it was not good enough for the practical application of the concept. This at the time was seen as a very serious limitation. For practical purposes, the locations of the events should be more accurate than 100–150 m, so that the apparent stress index contours could be related to specific faults, pillars, or underground working places. Because of this location-accuracy limitation, the region of Vaal Reefs was divided into blocks of 500 × 500 m. In order to test the validity of the concept, all event magnitude values in those blocks were divided into categories according to the

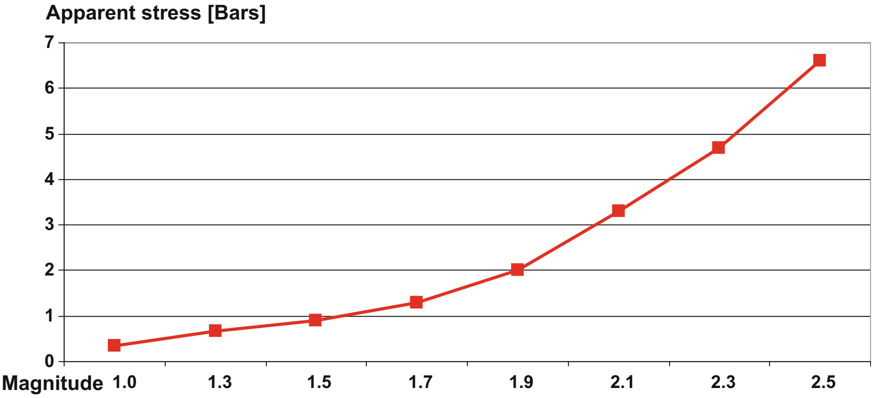


Fig. 3.1 Mean apparent stress values for different magnitude values

values of M_L as in Table 3.1. The apparent stress values were then used to plot the relation as shown in Fig. 3.1. For each block, and for every event within that block, the apparent stress index was calculated as the ratio between the measured value and the mean value. A mean of these values was then calculated, and its value was then attributed to the centre of relevant block. Contour lines were then drawn enclosing values of apparent stress index higher than 1.0, that is, where the values

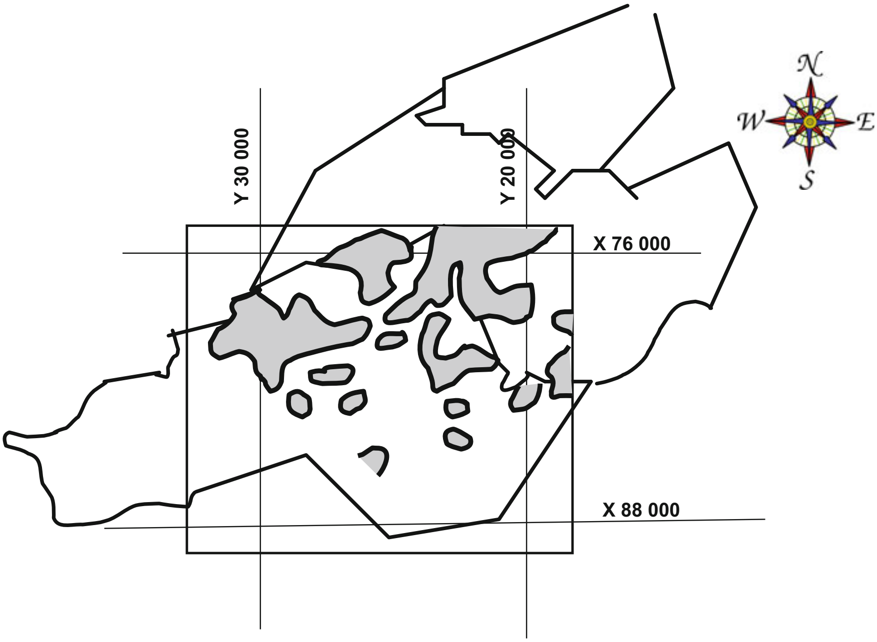


Fig. 3.2 Contour plots of apparent stress index (1990)

of apparent stress were higher than the mean. Figure 3.2 illustrates the result. The shaded areas are those where the values of the apparent stress index are above 1.0. The white areas consist of those regions where the values are lower than 1.0 and of those areas where there were no observations. Analysis of this map indicates that the shadowed areas in general cover a lot of ground around No. 5, No. 4 and No. 2 shafts, and these were known to be areas of high rock-burst hazard.

It was then concluded that:

1. The first test proved the validity of the concept.
2. The concept of apparent stress index can be used for the estimation of rock-burst hazard directly and, indirectly, as a tool for support design.
3. Contour plots could be used to indicate not only areas with high stress, but, when plotted at regular time intervals, they should indicate changes in stress over time.
4. This method needed further development to become a practical tool to be used by the Rock Engineering staff.

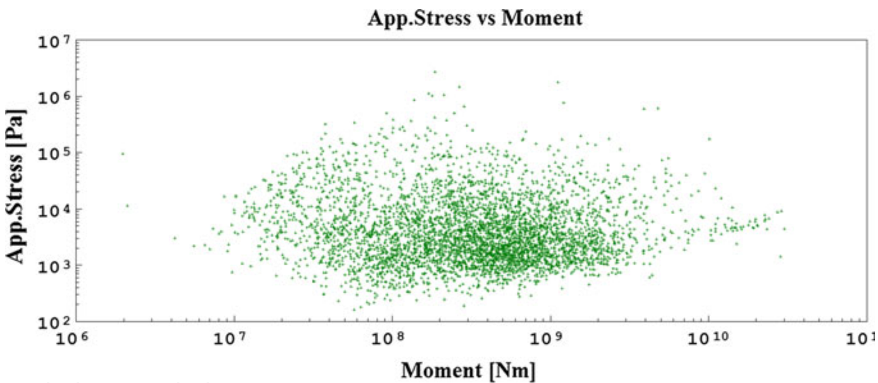
3.1 Apparent Stress Index and the Energy Index

It is obvious that the apparent stress index and the energy index are the same. These two indexes are based on energy and seismic-moment values. In the cases presented next, the input data for calculation of the indexes are the same. This is logical as the same index based on two different inputs will result in two different outcomes. This example is based on the seismic catalogue for two months, March and April 2005, that consists of 4454 events. The largest event of this catalogue had a magnitude 0.6.

Figure 3.3 illustrates the relationship between the seismic moment and apparent stress index. From this figure, it is evident that one seismic-moment value can have a wide range of apparent stress values. Figure 3.4 illustrates the relationship between seismic moment and seismic energy. Again, one value of seismic moment has a wide range of seismic energy values. As these two figures are based on the same input data, the seismic moment ranges of these two figures are exactly the same.

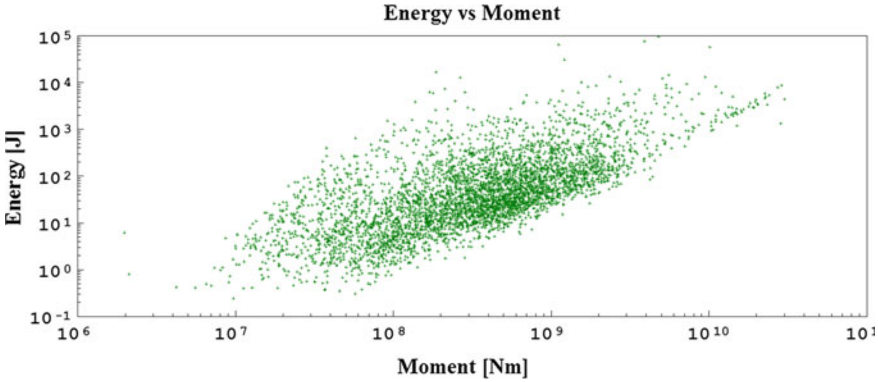
Figure 3.5 illustrates two time histories, i.e., of energy index (red) and of apparent stress (black). The smoothing parameters used for plotting of the two time histories are exactly the same. The absolute value range for the energy index is lower than for the apparent stress index. In spite of this, the two curve shapes and their trends are identical. When the first decreases, the second decreases, and when the first increases, the second also increases. Both graphs are telling the same story.

Figure 3.6 illustrates the same two parameter time histories, but the smoothing parameters used for plotting the two time histories are different from those used for presenting the time histories as in Fig. 3.5. As there is more smoothing in this second set of indexes, their maximum values are lower than in the first case. Still, the maximum for the energy index is lower from the maximum for the apparent stress. The slope of the increase in the second graph is not as steep as it is in the first



01/03/2005 – 30/04/2005
Mag>-3.0 Min 4 Sites
Min.Mag = -2.2 Max. Mag = 0.6
4454 Events
First 01/03/2005 00:21:28
Last 30/04/2005 23:59:17
Z: 400m down to -1700m Area 5.50 km^2

Fig. 3.3 Seismic moment versus apparent stress values



01/03/2005 – 30/04/2005
Mag>-3.0 Min 4 Sites
Min.Mag = -2.2 Max. Mag = 0.6
4454 Events
First 01/03/2005 00:21:28
Last 30/04/2005 23:59:17
Z: 400m down to -1700m Area 5.50 km^2

Fig. 3.4 Seismic moment versus seismic energy

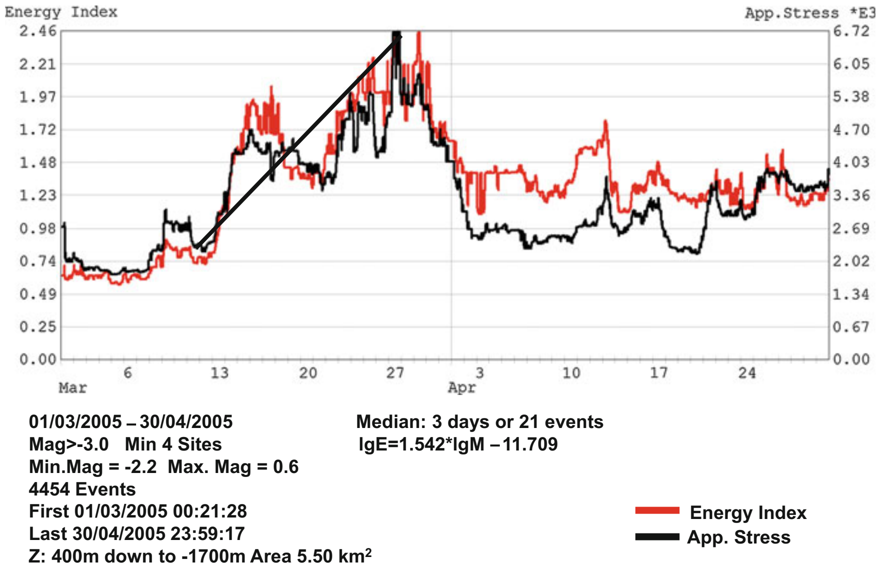


Fig. 3.5 Apparent stress and energy index time histories

graph. Due to more smoothing in the second set, the maximum values are shifted in time (forward) in comparison to the first set. This comparison, apart of proving that the energy index and the apparent stress are the same, indicates that their maxima and slopes are directly dependent on the smoothing parameters.

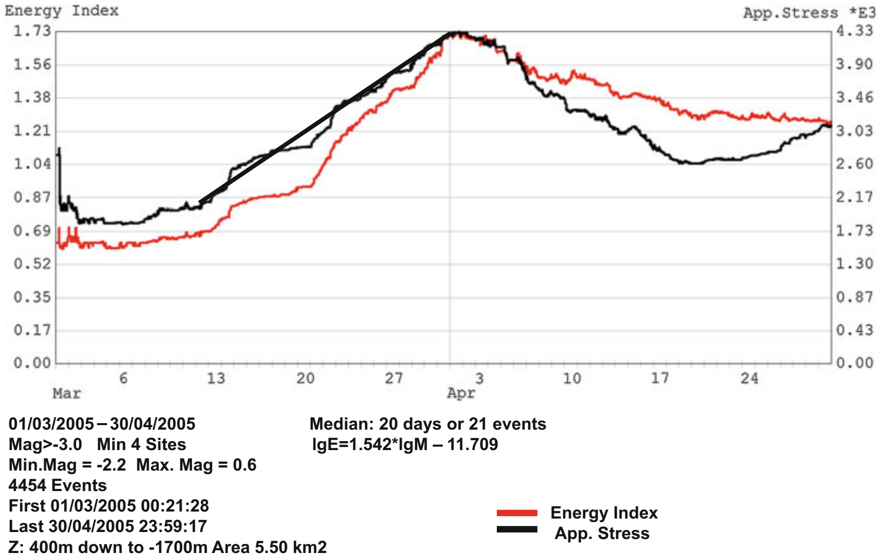


Fig. 3.6 Second versions of apparent stress and energy index time histories

3.2 Development of the Apparent Stress Index Concept 1991–1992

During the first months of 1991, I tested two different approaches to using the concept of apparent stress for plotting damage potential due to the occurrence of seismic events. The first approach was the development of the methodology itself. The second approach was different, and it involved plotting contour lines of apparent stress values for various categories of seismic moments or magnitudes.

3.2.1 Contour Maps of Apparent Stress Index

In this case, the mean value of apparent stress was calculated for every one of the eight categories of magnitudes ranging from 1.0 to 2.7. Every category of magnitude was then taken with an envelope of ±0.2. For example, M_L = 1.0 means all events from 0.8 to 1.2, M_L = 1.3 means all events from 1.1 to 1.5, etc. The results are presented in Table 3.1. Figure 3.7 presents the relationship between magnitude and the logarithm of apparent stress. Data used to establish this relationship was recorded between the end of May 1990 and up to 15 December 1990. The resulting regression-line fit is:

$$\mathrm{Log}_{10}\sigma a[\mathrm{Pa}] = 3.8352 + 0.7352 \times \mathrm{M_L}$$
$$\text{and the value of the correlation coefficient is } \mathrm{r} = 0.999$$

These mean values were then used to plot a map of the apparent stresses index. In order to draw this map, the entire Vaal Reefs area was divided into squares with a

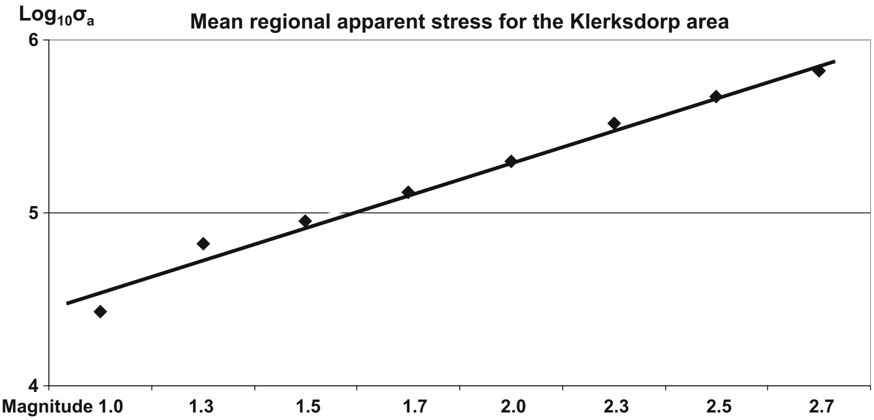


Fig. 3.7 Plot of magnitude versus log (apparent stress)

side of 500 m. All the events in these squares were divided into categories of events as in Table 3.1, and then a mean value of apparent stress for every category was calculated. The final value that was used for plotting was the mean value, calculated from all recorded categories in a given square. This mean value was then attributed to the centre of the square. The next step was to draw contours for values 1.0 and 1.5. Value 1.0 means that the measured value (the value for the square) is equal to the mean value. For areas where the apparent stress index is above 1.0, the measured value is higher than the mean value. Where the apparent stress index is below 1.0, the measured value is lower than the mean value. The higher the index, the higher would be the damage potential resulting from a seismic event. According to the resulting map (Fig. 3.8), there were a few areas (hot spots) for which the value of apparent stress index had values above 1.5. These "hot spots" were:

- No. 5 Shaft parts of 5B, 5D and 5G areas.
- No. 2 Shaft parts of 2A and 2K areas, corner of 2B, 2H, 2P and 2J areas.
- No. 8 Shaft part of 8G area.
- No. 1 Shaft part of 1D area.
- No. 3 Shaft parts of 3I, 3K and 3X areas.
- No. 4 Shaft part of 4B area.

All the above areas are surrounded by contours for which the values of apparent stress index were equal to 1.5. There are also places where contours enclosing values above 1.0 do not culminate in values above 1.5 (for example, the 9D area).

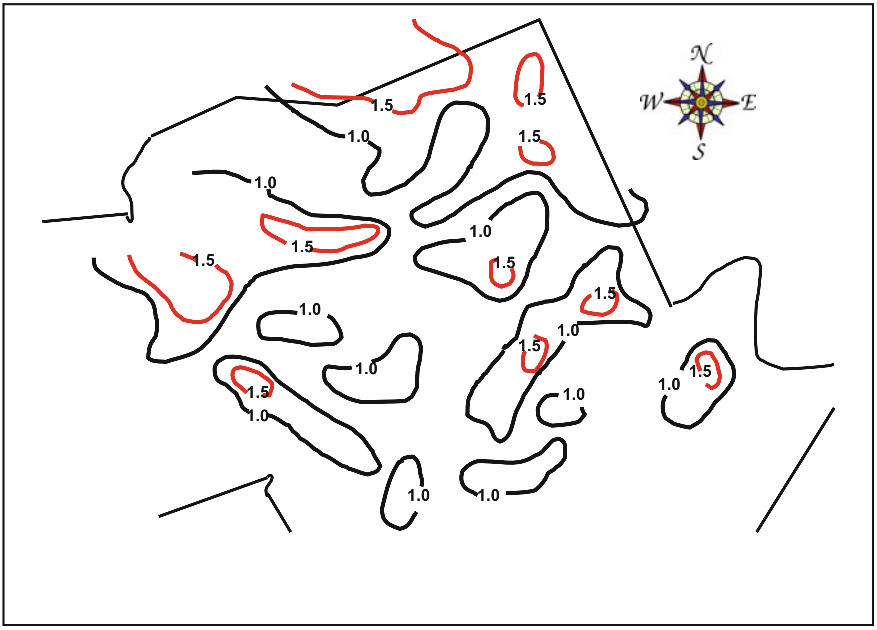


Fig. 3.8 Contour plots of apparent stress index (contours 1.0 and 1.5)

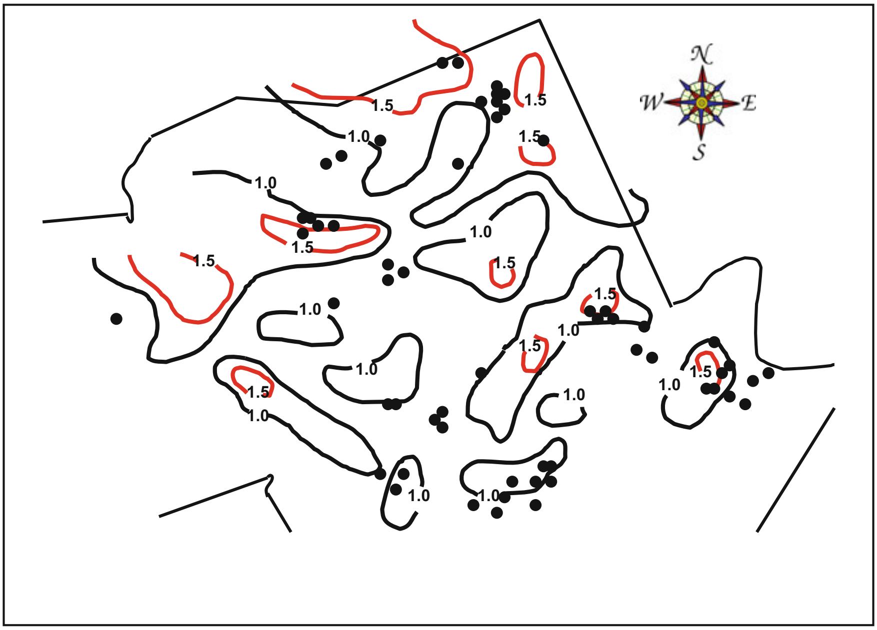


Fig. 3.9 Locations of fatalities and lost blast due to seismicity

The above approach is simple and implies that, at least in every square, the rock mass is homogeneous, and that all the events are the result of the same source mechanism.

A simple way of testing the accuracy and the correctness of the concept was to plot all known lost blasts or fatalities due to seismic events. This is presented in Fig. 3.9, on which all known lost blasts and fatalities are marked.

Areas where the lost blasts and fatalities due to seismicity coincide with maximum values of the apparent stress index (as on Fig. 3.8) were:

8E and 8G areas
9D area
2D area
5B area
1D/3K area

This cannot just be a coincidence. More data would still be required to test the correctness of the approach, but, from what was known at the time, it proved that the concept of apparent stress index, when fully developed, could be a very useful tool in dividing the mine into rock-fall and rock-burst areas. The approach as described above involved the use of magnitudes. In the case of the KMMA Regional Seismological Network, this magnitude was calculated from the value of the seismic moment. Therefore, it would be possible to base the derivation of the index on the relationship between seismic moment and apparent stress. This would

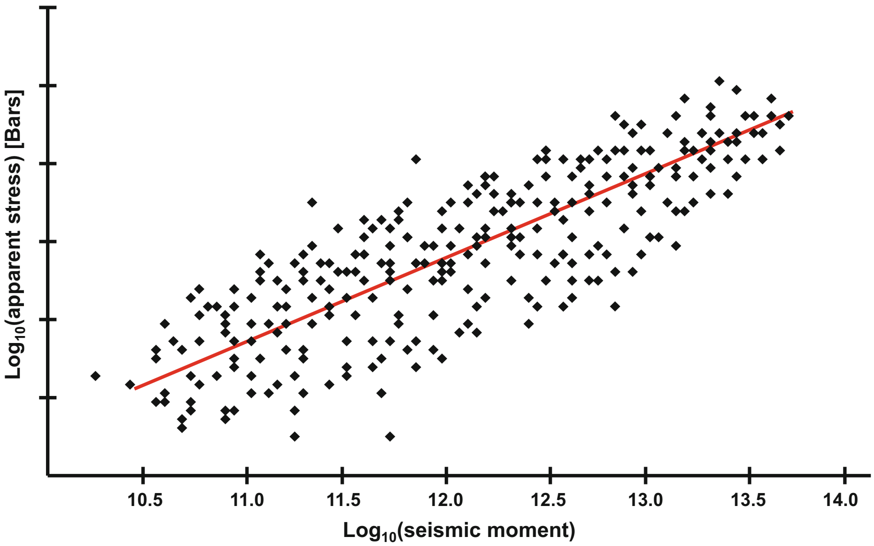


Fig. 3.10 Log (moment) versus log (apparent stress) for the Klerksdorp Area (1991)

change nothing in the concept of apparent stress index. This relationship for the Klerksdorp area is presented by Fig. 3.10. The regression line is given by: $\mathrm{Log}_{10}\ \sigma a$ (Bars) = $0.5406\ \mathrm{Log}_{10}\ \mathrm{Mo} - 6.0725$.

3.2.2 Contour Maps of Apparent Stress Values

The values of mean apparent stress in relation to the magnitudes are given in Table 3.1. It is a fair assumption that the larger magnitude events, those above 2.5, are connected with faults, whilst most of the smaller ones, in the ranges 1.0–1.5, are associated with working places. For this reason, all recorded events to date were divided into two categories:

- Category I: Events of magnitudes from 1.0 to 1.5
- Category II: Events of magnitudes from 2.5 to 2.7

Plotting and contouring apparent stress values for events of category I should highlight working areas that have a high potential for damage resulting from seismic events. In the case of category II events, the contours should highlight the faults cutting the Vaal Reefs gold mine. By mid 1990 the main limitation of this method was the amount of data that was available. Only 44% of the recorded data fit into category I, whilst in category II the figure was only 15%. For this reason, I had to include in category II all events from and above magnitude 2.0 (39% of all recorded events). The second limitation, i.e., a consequence of the first one, is that

Fig. 3.11 Contours of apparent stress for magnitude range 1.0–1.5

the method was based on a grid of 500 × 500 m. This is the reason why the next two maps are to be treated only as preliminary ones with no intention of using them for more detailed interpretation. Their main purpose was only to test the validity of the hypotheses. The future application of these types of maps would be to use them to compare various areas of the mine with each other.

Contours of apparent stress of seismicity magnitude range 1.0–1.5 are presented by Fig. 3.11. The contours are expressed in units of bars. According to Table 3.1, for $M_L = 1.5$, the mean value of apparent stress is about 0.9 bars.

In general, contours and the location of the maximum values on this map agree with those on the map given Fig. 3.8. At some places the fit between those two maps is good, as far as the location of maximum is concerned, for example, at:

- 5B and 5G areas
- 2K and 2J areas
- 8G area
- 4D and 4B areas
- 3V and 3W areas

These results indicate that this method could be useful once there is a sufficient amount of input data available.

Contours of apparent stress for magnitude ranges 2.0–2.7 are presented by Fig. 3.12. The contours enclose areas where the value of apparent stress is above 5 bars. According to Table 3.1, the mean value for the entire region for magnitude 2.7 is 6.6 Bars and 4.7 Bars for magnitude 2.0. Some of the data that was used to

Fig. 3.12 Contours of apparent stress for magnitude range 2.0–2.7 1991

produce this map should not have been used, for reasons already stated. But, in spite of this, the resulting map shows clearly four main faults cutting the Vaal Reefs area in the general direction NE–SW. This is not their exact location because of the data I had to use, and the 500 × 500 m grid.

3.3 Examples of Applications of the Stress Index Concept (1991–1993)

By the end of 1993, a significant amount of work was done at the Klerksdorp Regional Seismic Network in order to test the apparent stress index concept. Up to 1992, it was of no importance how many stations recorded an event. It was clear that, when more stations recorded the event, the more stable would be the estimated source parameters. Data used for the tests originated from a regional network that covered more than 200 km^2. Only later, it started to evolve into several shaft networks combined together, within a regional frame. More geophone stations were added as time went on. Work during 1990–1993 was concentrated mainly on developing methods for data interpretation. Results obtained at that time were used to change the network configuration and were regarded as good enough by management to invest more capital into the network and its extension. In the next sections are listed some examples of seismic data analysis and interpretation from that time.

3.3.1 Back Analysis of a Large Seismic Event that Occurred on 1 December 1991 at No. 5 Shaft Vaal Reefs

On the first of December 1991 at 22:03:23, a large seismic event took place. This event was located close to the intersection between the No. 5 Shaft Fault and the Clemcor Dyke. The energy magnitude of this event was 5.2. It is interesting to note that this event was not recorded by any of the stations located at No. 5 Shaft. This was due to the fact that power was lost in most of the shaft areas. The closest station that recorded this event was an underground station located at Hartebeestfontein G. M. The distance between this station and the source location was 2700 m in a northerly direction. The recorded peek ground velocity was 0.1 m/s. The station that was located at No, 2 Shaft Vaal Reefs and south of the event at a similar distance recorded a maximum amplitude of 0.4 m/s. Figure 3.13 indicates the network configuration at that time. The Vaal Reefs No. 5 Shaft was located in the centre of the presented map.

During the period starting 2 September 1991 to the time that this event occurred, for the area between Y = 25,000 and 23,500 and X = 75,000 and 78,000, that is in an area of 1500 × 3000 m, 586 events have been recorded. The area includes the shaft pillar. It can be assumed that locations of these events were accurate because this area was in the centre of the network and was surrounded by several geophone stations, located both on the surface and underground. Figure 3.14 shows the

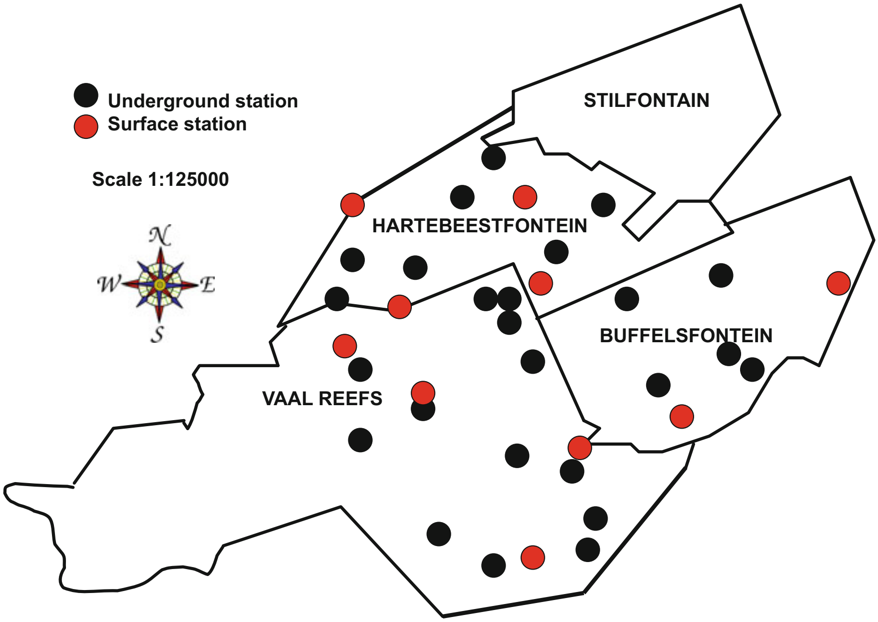


Fig. 3.13 KMMA regional seismic network configuration at December 1991

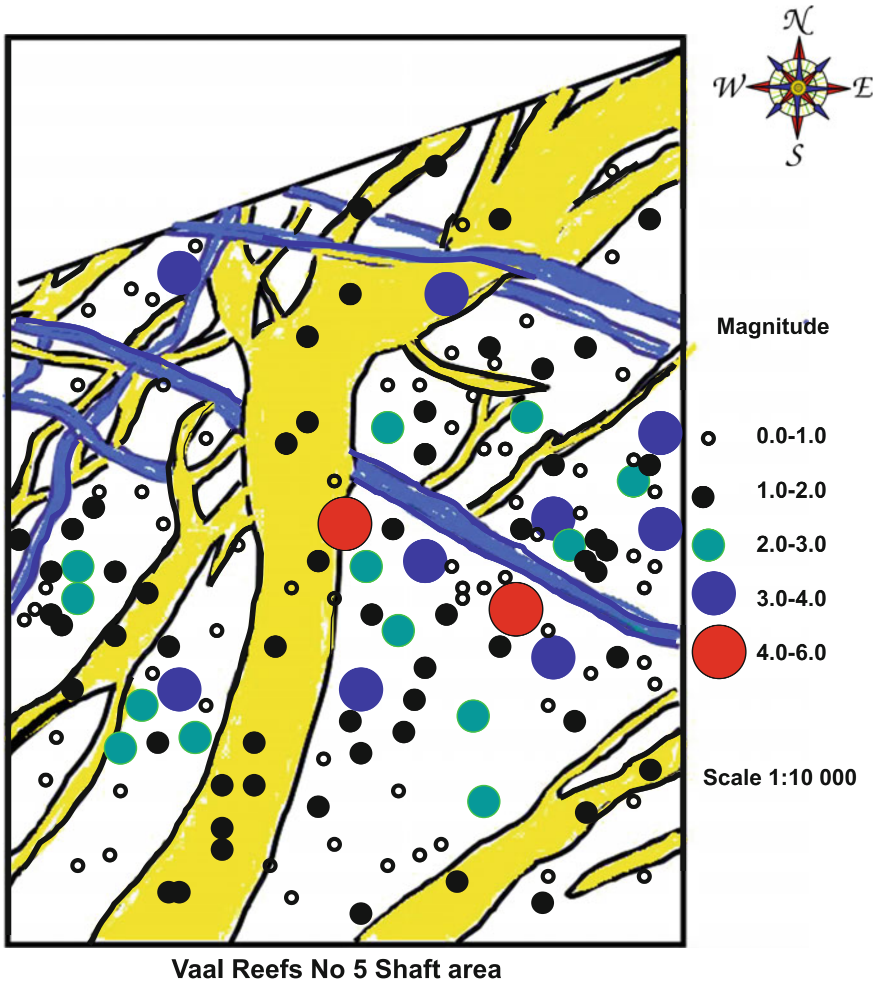


Fig. 3.14 VR No. 5 Shaft events—magnitudes

magnitude distribution of those events. These events were recorded between 2 September 1991 and 1 December 1991. An event of magnitude Me = 5.2 is located at the centre. There is a concentration of events to the east of this event. The plot of these events' apparent stress values indicates that there was a concentration of events with high apparent stress values close to the big event along the dyke. Figure 3.15 illustrates the values of apparent stress index of these events. In general, all events to the east of the fault are with index values above 2.0.

Figure 3.16 illustrates the location of seismicity at No. 5 Shaft recorded before the large event took place between 2 September 1991 and 1 December 1991 (stress index values). Figure 3.17 illustrates the contour plots of stress index before the

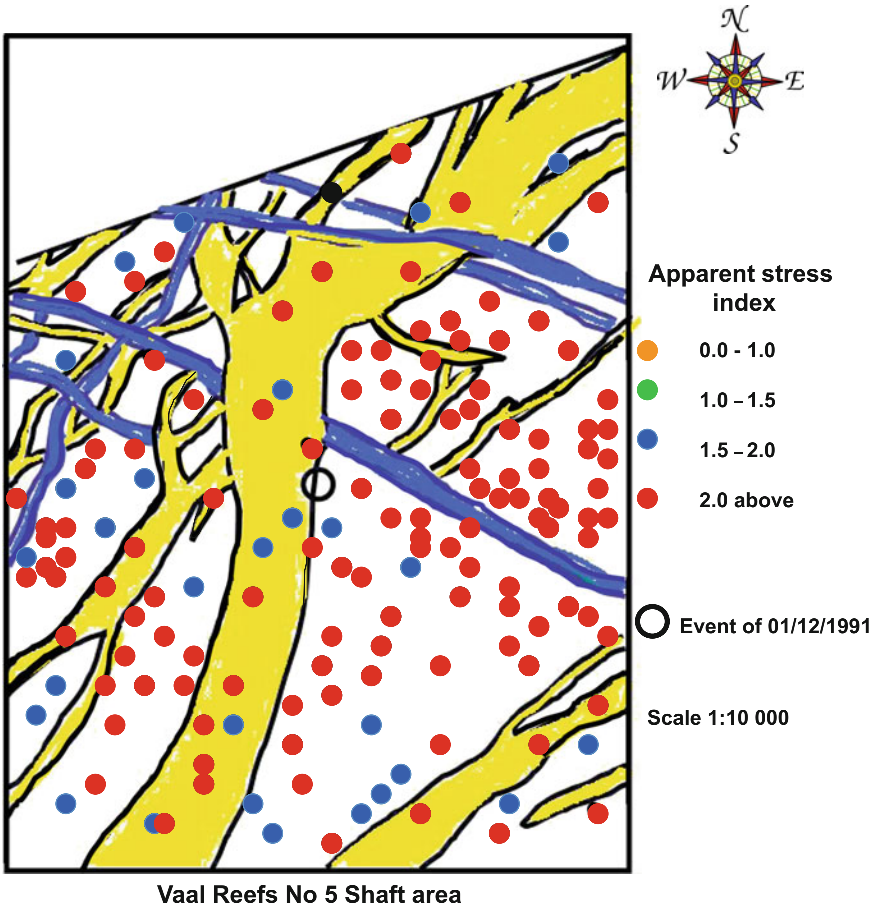


Fig. 3.15 VR No. 5 Shaft events—apparent stresses index

magnitude 5.2 event at No. 5 Shaft Vaal Reefs. Figure 3.16 indicates that, in general, the whole area was highly stressed. Based on an analysis of several similar events, it became clear to me that the large events are not necessarily connected with the highly stressed areas, but rather take place in areas where there is a significant gradient of those stresses—on the border between the areas of high and low stress. Part of the regional map on which I plotted those events covering the area of interest is presented in Fig. 3.17. Note that, in general, the fault-loss areas are surrounded by high-value contour lines, and that the gradient on those boundaries is high. The “O” indicates the event location. Data used for this map was recorded between 1 September 1990 and 4 November 1991. The events located close to the shaft show that their apparent stress index values were high.

Analysis of seismicity in this area recorded after the large event of 1 December 1991 up to 12 December 1991 indicated that this event did not release all the

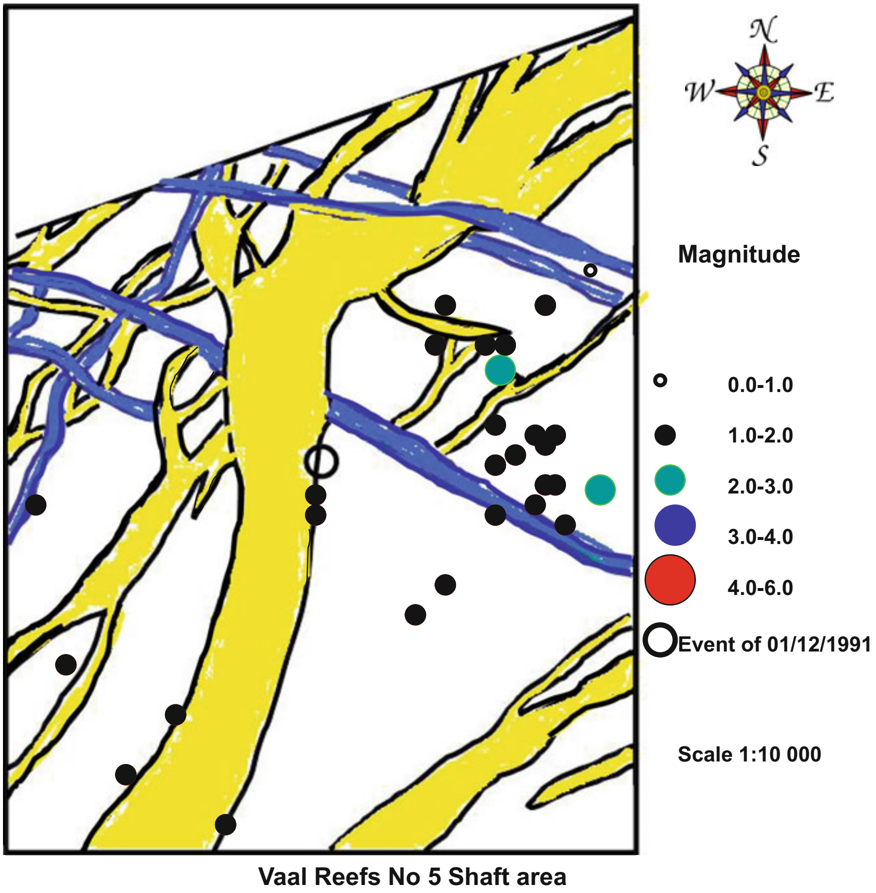


Fig. 3.16 VR No. 5 Shaft—magnitude values

stresses in the area. The apparent stress index values were still very high. It was not possible to conclude, at that time, if the area was ready to experience another large event. Still, such a possibility could not be excluded. Especially worrying were the high values of apparent stress index of the events located very close to the shaft. It is interesting to note that the next big event in the same location took place in February 1997. This event is discussed in Sect. 4.11 and was already mentioned in Sect. 2.4. At that time, it was concluded that, apart from the need for more seismic stations at No 5 Shaft Vaal Reefs, there was an urgent need to scale down the apparent-stress-index procedure from regional to local applications and that the seismic data should be integrated with rock engineering, mining, and geological information.

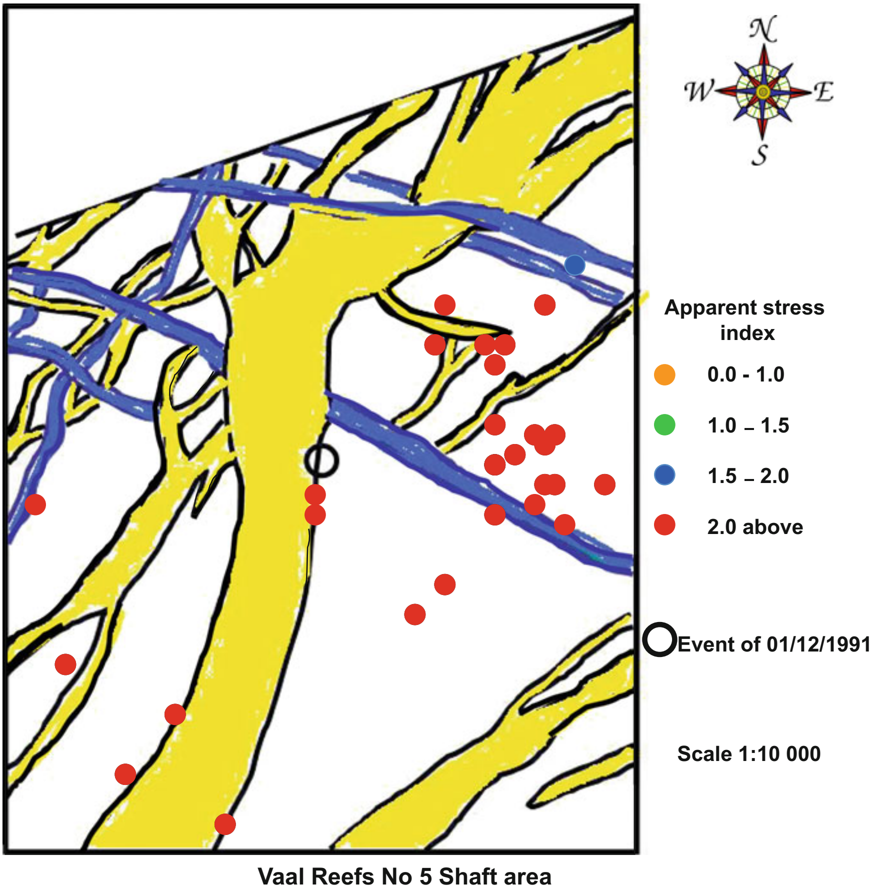


Fig. 3.17 VR No. 5 Shaft—stress index values

3.3.2 Interpretation of Seismic Data Recorded in the Vicinity of the Clemcor Dyke from September 1990 to September 1991

The Clemcor Dyke had a known history of being seismically active, resulting in fatal accidents and damage. For interpretation purposes, data recorded between 1 September 1990 and 31 March 1991 in a polygon of 400 × 400 m was taken into account. During this time period, 46 events were located inside this polygon. Values of apparent stress index were analysed in two ways:

- By studying their value changes with time
- By studying their contour plots.

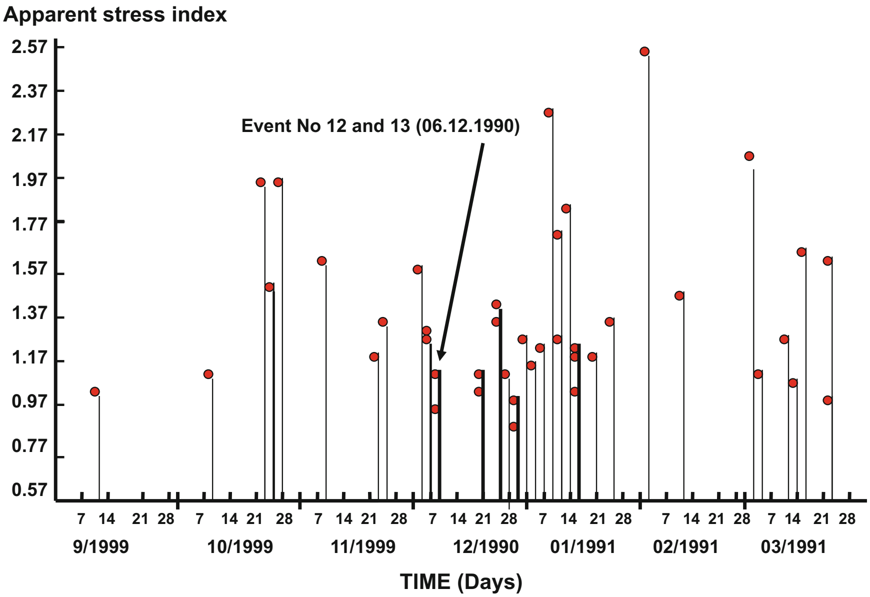


Fig. 3.18 Apparent stress index time history

Figure 3.18 illustrates the distribution of the apparent stress index in time. In fact, this had to be the first plot of the index time history. The events that resulted in loss of life took place on the 06 December 1990 (events Nos. 12 and 13). For these events, the apparent stress index was equal to 1.1, indicating that it had dropped from the value of 1.5 which existed there for event No. 8 at the beginning of the month.

Figure 3.19 illustrates the contour map of apparent stress index in the vicinity of the Clemcor Dyke.

A grid of 40 × 40 m was used to produce this plot. This plot indicates:

1. That nearly the whole area in close vicinity of the dyke has high levels of stresses (values above 1.5)
2. The contour value of 2.0 surrounds the dyke, while on the dyke itself the contour values are 2.2 and 2.5.

There was a very good correlation between the dyke position and the contour lines. Data recorded in the polygon from the fatal events of the 1 March 1991 to the 22 March 1991 were then used to try and establish if the area was already safe to continue with the development work through the dyke. For this, the so-called apparent volume was used (Mendecki 1993, 1997). Apparent volume is defined as:

$$\mathrm{VA} = \mathrm{M_o}/2\sigma_\mathrm{a} = \mathrm{M_o^2}/2\mu\mathrm{E}$$

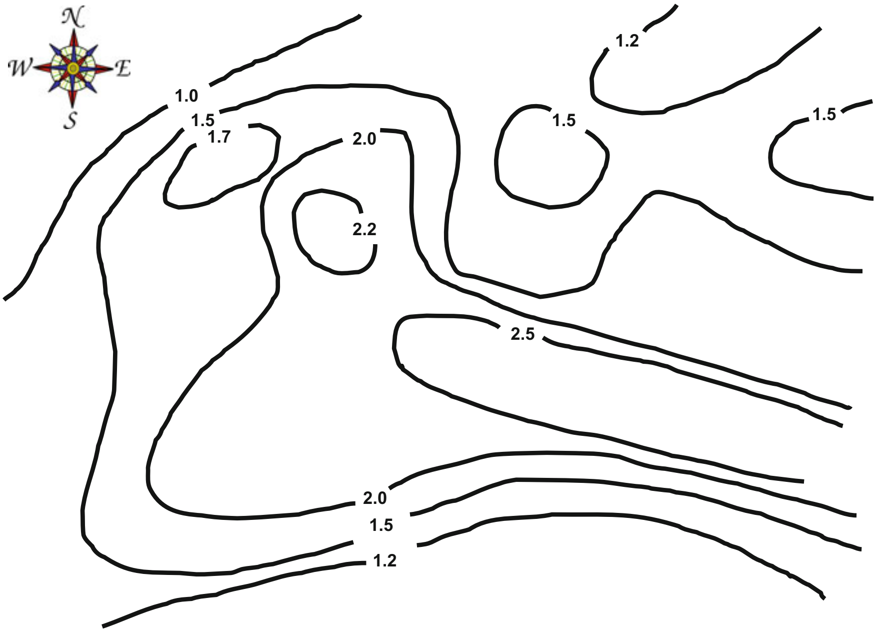


Fig. 3.19 Contour lines of apparent stress index

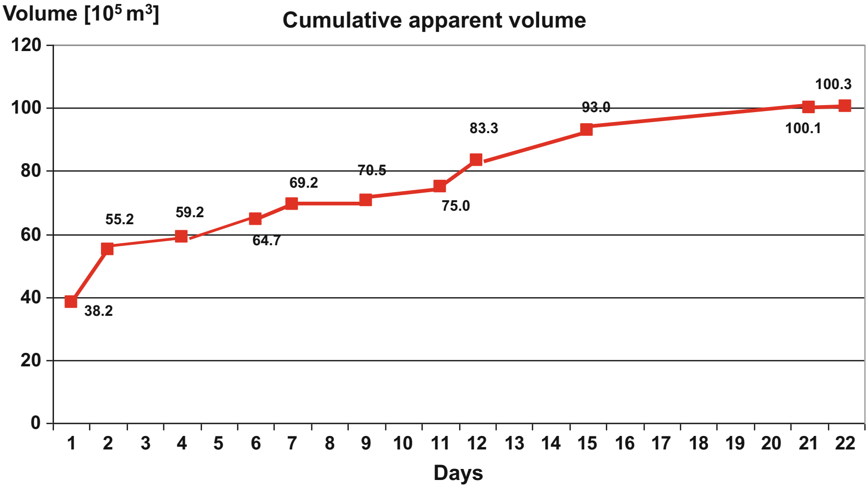


Fig. 3.20 Cumulative apparent volume in the rock mass volume around the dyke

Apparent volume depends on the seismic moment (M_o) and radiated seismic energy (E), just like the value of apparent stress (σ_a). Apparent volume can be interpreted as the source volume or volume of rock mass that, because of fracturing, was de-stressed during the event. Figure 3.20 illustrates the cumulative value of apparent volume from day 1 to day 22. The maximum of the vertical scale is the volume of rock mass, which was calculated using the area of the polygon multiplied by the difference in depth between the deepest and shallowest events.

Because the ratio between the cumulative apparent volume and the rock volume on the 22nd day after the accident was about 0.85, it was assumed that the dyke in the close vicinity of the development end was de-stressed and it was safe to continue with the mining. It is clear that this interpretation method has a great potential and is extremely important in mining practice. In conclusion, this analysis indicated that:

1. Before the occurrence of larger-sized event, there are some significant changes in the value of the apparent stress index
2. Cumulative apparent volume has a potential to be used to monitor the amount of de-stressed rock volume
3. There is a great potential for this type of data interpretation, providing that the underground working places that are in rock-burst conditions receive better seismic cover

3.3.3 Back Analysis of a Large Seismic Event that Occurred on 19 June 1992 at No. 9 Shaft Vaal Reefs

On 19 June 1992 at 9:26:19, an event of energy magnitude 4.4 occurred at No. 9 Shaft. This event was located on the reef elevation, only 300–400 m from the working places. The event resulted in a fatality and significant damage to the underground working places. Figure 3.21 illustrates the contours of the apparent stress index as on 22 March 1992 (two and a half months before the event). The location of the 19 June 1992 event is marked with a red circle. It is located where the gradient of the stress index is high. The loss of life and extensive damage occurred at places denoted by A, B, C, and D (inside of the red oval), close to the contour value of 1.3. Figure 3.22 shows the same area, but with contour lines of the stress index updated to 19 June 1992. There are not many changes, which indicated that the amount of seismicity between the end of March and the middle of June was low. The main change is that the value of the contour line close to the accident increased from 1.3 to 2.1, and a high contour value of 6.0 occurred south of the working place.

These two contour maps are based on grids of 100 × 100 m. As the seismic cover in this area wasn't too good, it must be assumed that some small events with magnitude below 1.0 were not recorded. Figure 3.23 shows the same area but this time with contour lines based on grids of 250 × 250 m. These contour lines are based on maximum values of stress index for events that were recorded up to February 1992. In fact, this is part of the regional map of apparent stress index contours which, at the time, was updated once a month. According to this figure, the event occurred on a contour value of 1.5, and the accident and damage took place in the area where the values of stress index were between 1.5 and 2.0. Lines denoted 34–41 are the numbers of the raise lines.

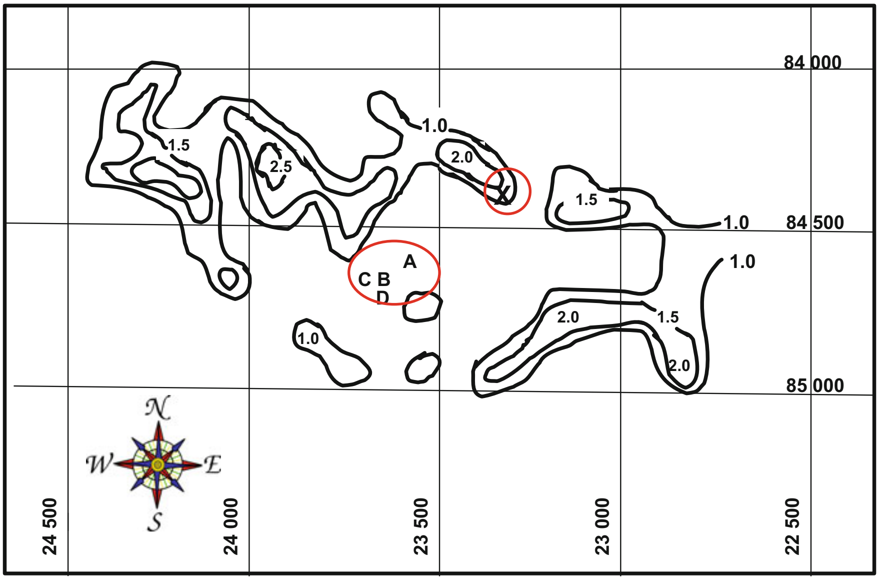


Fig. 3.21 Contour map of stress index on 22/03/1992

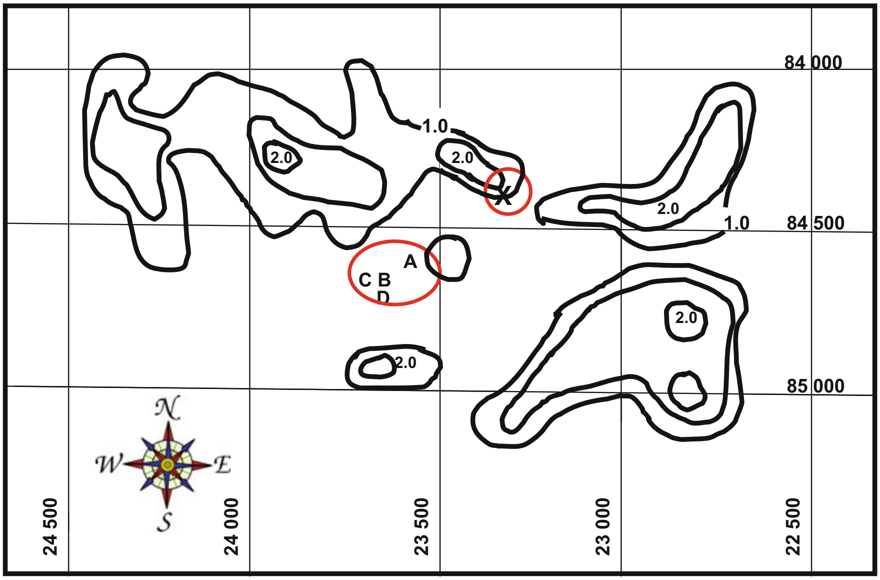


Fig. 3.22 Contour map of stress index on 19/06/1992

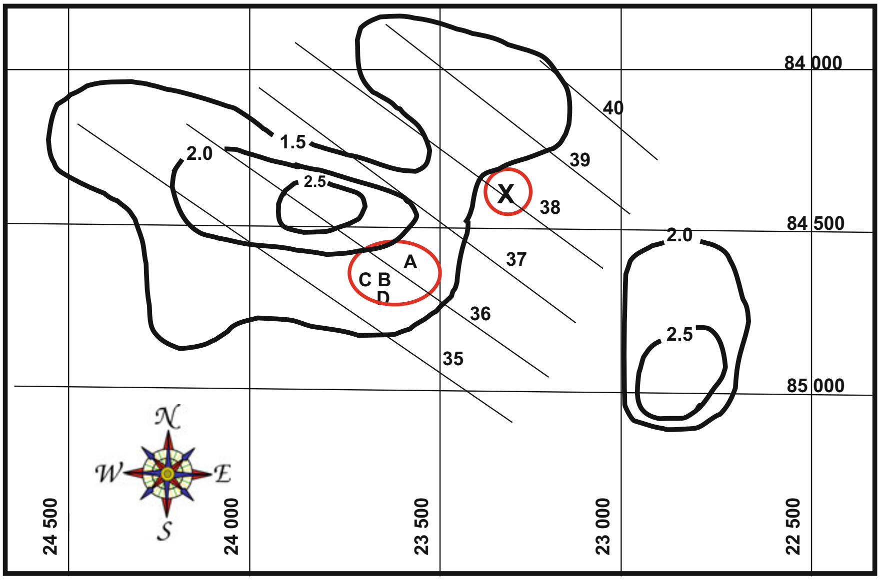


Fig. 3.23 Contour map of stress index—maximum values as by February 1992

At the time, it was concluded that this method of interpretation of seismic information has merit. It allowed for detecting and monitoring changes of the underground stress conditions with time. For this technique to provide useful information for the mine and Rock Mechanics personnel, it should be more detailed. For this reason, the density of seismic stations must be increased, at least in areas that experience seismic activity.

3.3.4 Comparison of Seismicity Between Filled and Conventional Mined Areas

To date, practically all available information about the influence of backfill on the nature of seismicity was based on studies carried out on the same area for a period before backfilling and then later, after extensive backfilling (Spotliswode and Churcher 1988; Adams et al. 1990; Hemp and Goldbach 1993). A new approach to such comparisons between filled and conventionally mines areas could be made with the areas covered by the Klerksdorp Regional Seismic Network due to the development in seismic data-interpretation techniques. The objects of comparison were two adjacent mining areas, one at Vaal Reefs and the other one at Hartebeestfontein at which the working places were, at that time, less than 1000 m apart. These two areas were of similar geology, and the same reef was mined at the same depth below the surface. The production volumes of these two areas were

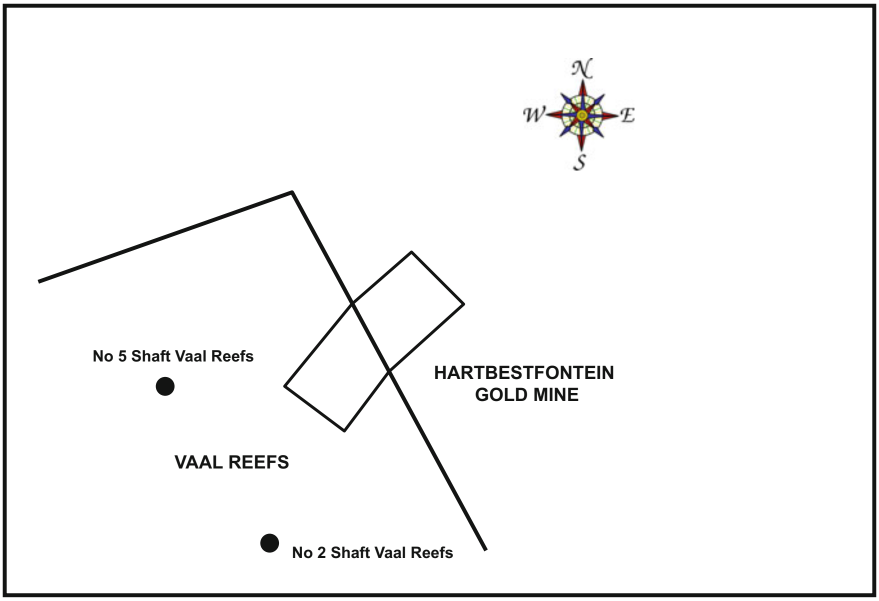


Fig. 3.24 Location of the areas at Vaal reefs and Hartebeestfontain

similar. The main difference between the two areas was the support. Backfill was used extensively in the Vaal Reefs area, while the area at Hartebeestfontein was mined with elongates and packs as temporary support. The seismicity in these two areas was monitored by the same seismic network with approximately the same coverage. Figure 3.24 illustrates the location of the two areas in reference to No. 2 Shaft Vaal Reefs. Those two blocks are approximately of the same 1.0 km^2 area. Seismic data that was used for this analysis was recorded between January 1991 and March 1993 (27 months). The production level, for the time between 01 June 1991 and 30 June 1992 was 84,735 m^2 at Vaal Reefs and 68,182 m^2 at Hartebeestfontein, so the production difference was about 20%.

Table 3.2 presents some characteristics of seismicity for the period of 27 months.

Table 3.2 Comparison of two areas, 2K Vaal Reefs and No. 4 Shaft Hartebeestfontein

Characteristic	Vaal Reefs block	Hartebeestfontein block
Total no. of recorded events	755	341
No. of events below magnitude 1.0	437 (57.8%)	180 (52.8%)
No. of events between magnitude 1.0 and 1.9	283 (37.6%)	133 (39%)
No. of events above magnitude 2.0	35 (4.6%)	28 (8.2%)
Cumulative seismic energy (J)	1.41E+10	1.49E+10
Cumulative seismic moment (Nm)	2.21E+14	2.12E+14

From the tabulated comparison, it is evident that for the same time period about twice as many of the events were recorded at the Vaal Reefs block compared to the Hartebeestfontein block. However, the magnitude distribution is about the same for those two blocks, with about 90% of the events being below magnitude 2.0. As small events do not contribute much towards the next two values listed in Table 3.2, namely cumulative values of energy and moment, it follows that these values are practically the same for the two blocks. Scaling relations, such as those between seismic moment and apparent stress, can be used to detect variations of the rock mass behaviour (Figs. 3.25 and 3.26).

Based on data shown in Fig. 3.25, the following relation was obtained:

$$\mathrm{Log}_{10}\sigma\mathrm{ah} = 0.72\ \mathrm{Log}_{10}\mathrm{Mo} - 7.85 \quad (\text{for Hartebeesfontain})$$

For the data shown in Fig. 3.26, the orthogonal regression results in the relationship:

$$\mathrm{Log}_{10}\sigma\mathrm{av} = 0.75\,\mathrm{Log}_{10}\mathrm{Mo} - 8.31 \quad (\text{for Vaal Reefs})$$

From these two values, it follows that: $\sigma\mathrm{ah}/\sigma\mathrm{av} = 10^{(0.46-0.03\ \mathrm{Log10\ Mo})}$ and:

$$\sigma\mathrm{ah}/\sigma\mathrm{av} = 1.31\ \text{for}\ \mathrm{Log}_{10}\mathrm{Mo} = 11.358\ (\text{equal to Mm} = 1.5)$$
$$\sigma\mathrm{ah}/\sigma\mathrm{av} = 1.12\ \text{for}\ \mathrm{Log}_{10}\mathrm{Mo} = 13.608\ (\text{equal to Mm} = 3.0)$$

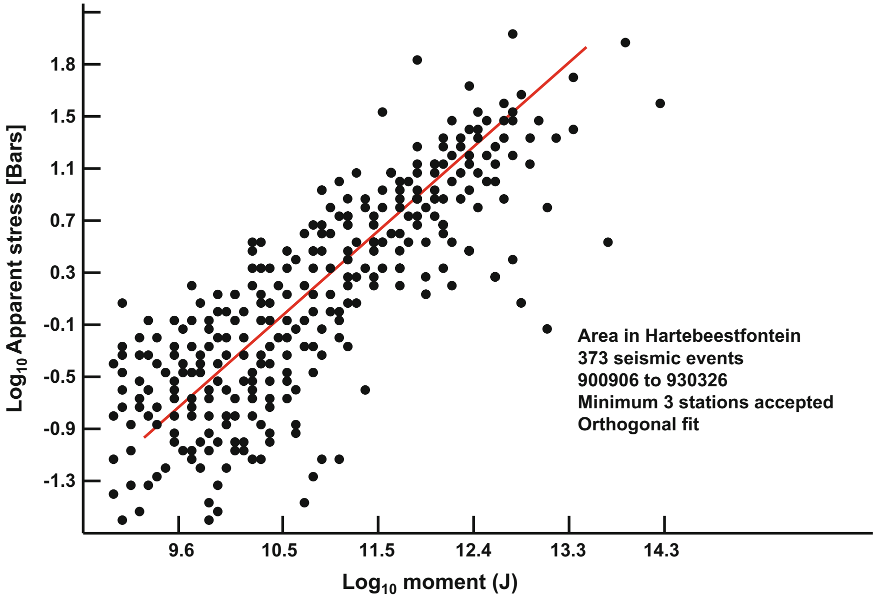


Fig. 3.25 Relation between seismic moment and apparent stress for the block at Hartebeestfontein (σah)

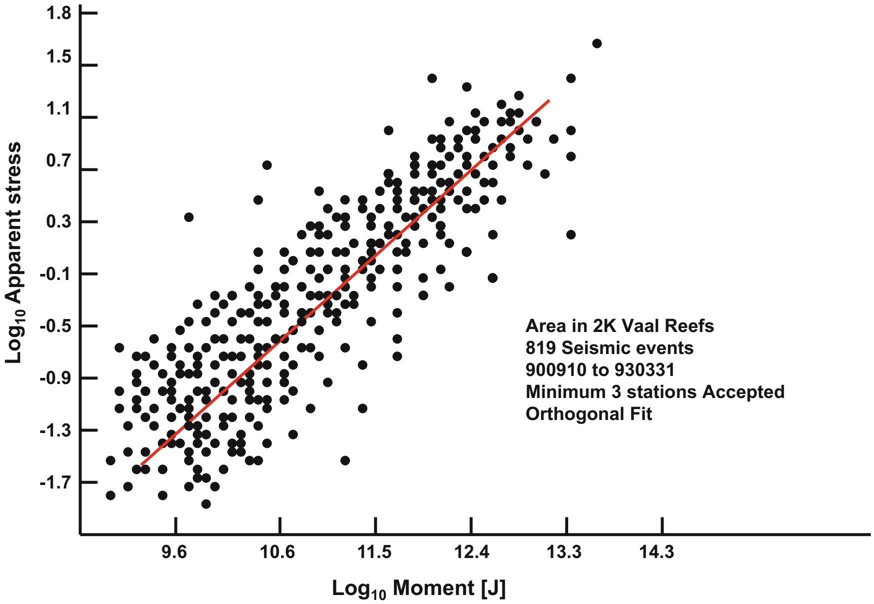


Fig. 3.26 Relation between seismic moment and apparent stress for the block at Vaal Reefs (σav)

where

σah apparent stress at the Hartebeestfontein block
σav apparent stress at the Vaal Reefs block
M_m moment magnitude.

It seems that the two scaling relations for the two mines are almost identical, as the ratio values are close to one. Apart from comparing the scaling relations for the two blocks, some estimation of hazard evaluation was made using the method described by Kijko and Sellevoll (1989, 1992). The largest possible event that can occur in the Hartebeestfontein block was estimated to be $M_m = 3.02$ and could be expected once every 17 years. To date, the largest event recorded was $M_m = 2.9$. The largest possible event that could occur in the Vaal Reefs block was estimated as $M_m = 2.9$ and could be expected once every 33 years. To date, the largest event recorded was $M_m = 2.8$. In conclusion, there is no difference in the seismicity between those two areas. It seems that the extensive backfilling on the Vaal Reefs side did not cause any major change to the nature of seismic events when comparing them to the adjacent block at Hartebeestfontein. This interpretation, done by a seismologist and then adopted by rock engineers, resulted in discontinuing with the backfilling in the Vaal Reefs block. This avoided considerable costs.

3.3.5 *Interpretation Possibilities of the Apparent Stress Index—Some Observations*

Often, standard interpretation methods used in global seismology are not sufficient for mining-induced seismicity. The approach to this type of data must be different. Results of interpretations should help in formulating recommendations that will improve underground safety and increase productivity. In other words, they must be of practical consequence to the mine. Apparent stress is independent not only of the magnitude but also of an assumed model for the source. Each recorded event is a measure of the stress. The amount of measured data will depend on only two factors: the amount that there is to measure and the amount that is made possible to measure. In deep gold mines of South Africa, there is no lack of seismic events—this is provided by the combined forces of nature and of mining itself. The seismic network can be configured in many ways, and it is up to its staff to find the optimum configuration. That will depend on local needs and the available capital. The events that have to be captured are the small ones. Their apparent stress values will indicate the level of underground stresses, which could then be used to determine the seismic hazard. In order to use a wide range of seismic events for interpretation purposes, it is essential to normalize them to a parameter of the same dimension, which, in the case of the apparent stress, will be its mean value. Figure 3.27 shows

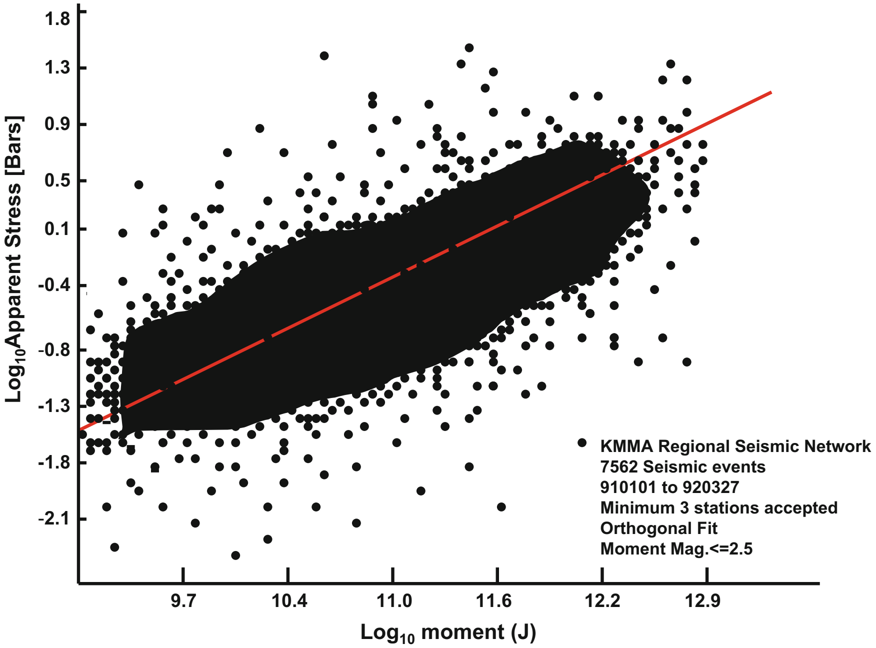


Fig. 3.27 Relation between seismic moment and apparent stress (1992)

the relationship between the seismic moment and the apparent stress values. It is based on more than 7500 seismic events. The upper value of moment is limited to the value of $\mathrm{Log}_{10}\,\mathrm{Mo} = 12.9$, which is equal to a moment magnitude of 2.5 (Hanks and Kanamori 1979).

Up to 1992, it was of no importance how many stations recorded an event. Figure 3.27 presents data recorded by three or more geophone stations. It is clear that, with more stations recording the event, the more stable should be its estimated source parameters. This could explain the larger scatter of data in the lower range of the moment values. The presented data originated from a regional network that covers over two hundred square kilometres. Only later, it started to evolve into several shaft networks combined together, within a regional frame. More geophone stations were added as time went on. Work during 1990–1993 was concentrated mainly on developing methods for data interpretation. Results obtained at that time were used to change the network configuration and were regarded as good enough by management to invest more capital into the network and its extension. Figure 3.27 illustrates the fact that, for one given value of moment magnitude, the apparent stress can vary over a large range. For example, the value of $\mathrm{Log}_{10}\,\sigma_a$ for $\mathrm{Log}_{10}\,\mathrm{Mo} = 11.0$ ranges from −0.8 to +0.6. This means that events of magnitude 1.3 can have a value of apparent stress from about 0.15 bars to as much as 4.00 bars—its value can vary by as much as 27 times. This is a clear indication that the magnitude is not the best parameter to describe an event. It makes events look the same, while in fact they are very different. Figures 3.28 and 3.29 illustrate this point. Figure 3.28 shows one of the areas monitored by the network, displaying all events with a moment magnitude equal to 1.5. These events were recorded during a time span of 20 months from 1 September 1990 to 20 April 1992. There is not much to be learned from this figure, apart from the concentration of the events, as all the events are of the same magnitude. Figure 3.29 shows the same set of events but this time expressed in terms of their apparent stress values. Now a different picture is presented, as those events differ from each other. It is clear that every seismic event is sending out its own message. One only has to capture it and then be able to translate it into a language that can be used by the miners.

Figure 3.27 illustrates the fact that relatively small events can be used to monitor seismic hazard. The regression line for the data displayed by Fig. 3.27 is:

$$\mathrm{Log}_{10}\,\sigma a\,(\mathrm{Bars}) = 0.73\,\log_{10}\mathrm{Mo} - 7.95$$

This regression line represents the mean value of apparent stress for the whole area. For example, if $\log_{10}\,\mathrm{Mo} = 11.0$, then the mean value of σ_a will be 1.1 bars. Lets assume that for a given event for which $\log_{10}\mathrm{Mo} = 11.0$ the measured value of apparent stress is 2.9 bars. In this case the ratio of measured value/mean value = apparent stress index will be equal to 2.6. This means that the level of underground stresses at the particular place of which the coordinates are known are higher from the mean. From the way that the stress index is calculated, it follows that:

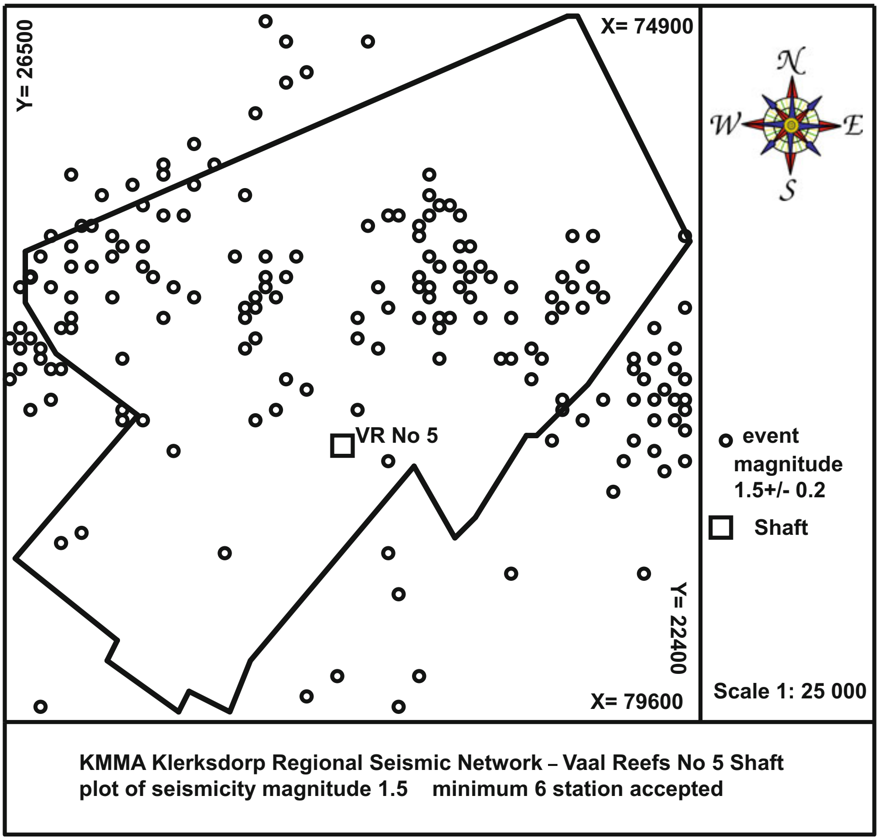


Fig. 3.28 VR No. 5 Shaft Seismicity of magnitude 1.5

1. If it is lower than 1.0, then the underground stress level is lower than the mean value.
2. If it is equal to 1.0, then the underground stress level is equal to the mean value.
3. If it is higher than 1.0, then the underground stress level is higher than the mean value.

In 1992, it was not possible to perform more detailed analysis on a regional, mine or shaft scale. The main problem was the large area covered by the network with insufficient number of geophone stations. Figures 3.30 and 3.31 present the same area of the mine. Figure 3.30 presents all recorded events using their magnitude values. These events were recorded between 1 September 1990 and 20 April 1992. The two working areas are where there are two main concentrations of events. The one on the lower left hand side of this region, generally has lower magnitude events, while the one on the top right has more events at the higher end of the moment magnitude scale. The first working area experienced, in general, more

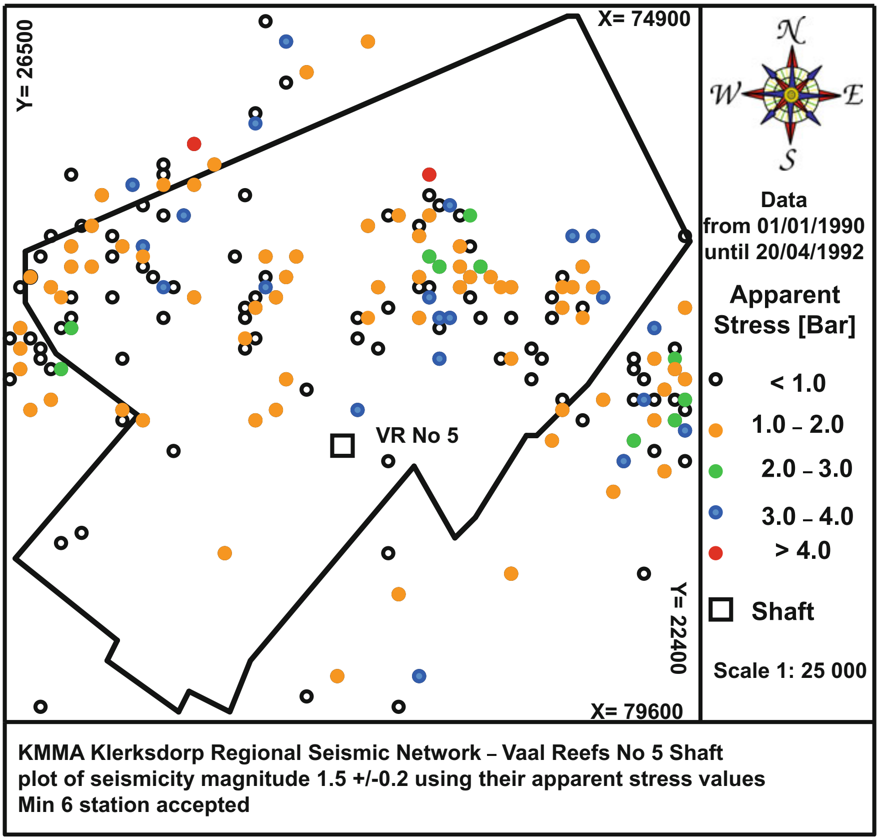


Fig. 3.29 VR No. 5 Shaft Seismicity magnitude 1.5 (apparent stress)

underground damage than the second one. Figure 3.30 does not explain the reason for this fact. Looking at this figure, one would expect that the situation would rather be reversed.

Figure 3.31 illustrates the reason for this situation. The same events are plotted but this time using their stress indices. For most of the events in the first area the stress index is above 1.5 or above 2.0, while in the second area, most of them are below 1.5. Figure 3.31 might explain the reason for underground damage, but apart from this, it has no further practical applications. There are areas of the mine for which we record more than 100 events per month, so plots like this would not help much, as they would be difficult to interpret. It would be better to monitor changes in the stress index values with time, and be able to observe the trends. This could be a viable possibility, but difficult or impossible to put into practice in a scattered mining environment, with a regional network as a tool. Still it might be an option for future use, with a network dedicated to monitor only a very small area. Other options include plotting contour lines using selected data. There are two options.

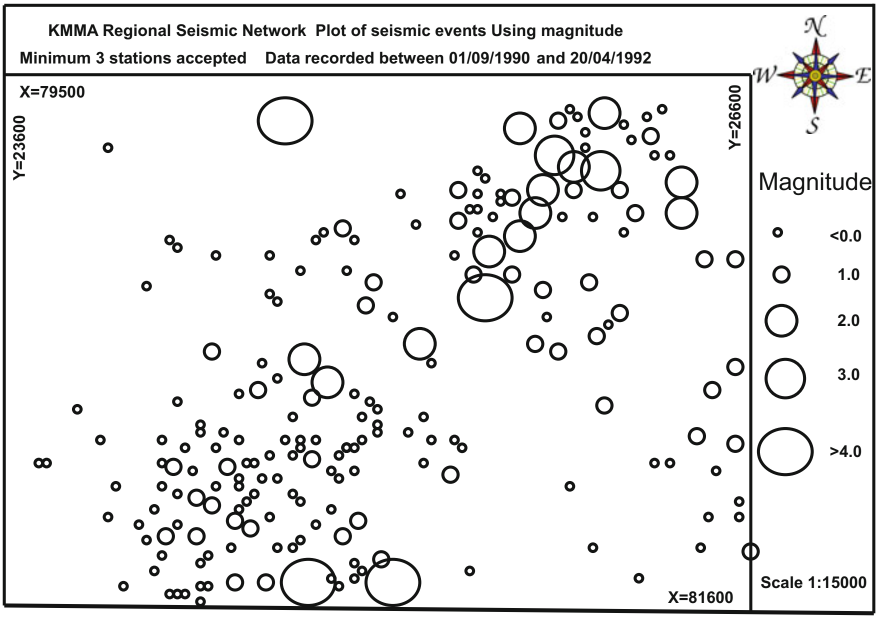


Fig. 3.30 Plot of all recorded events using their magnitude values

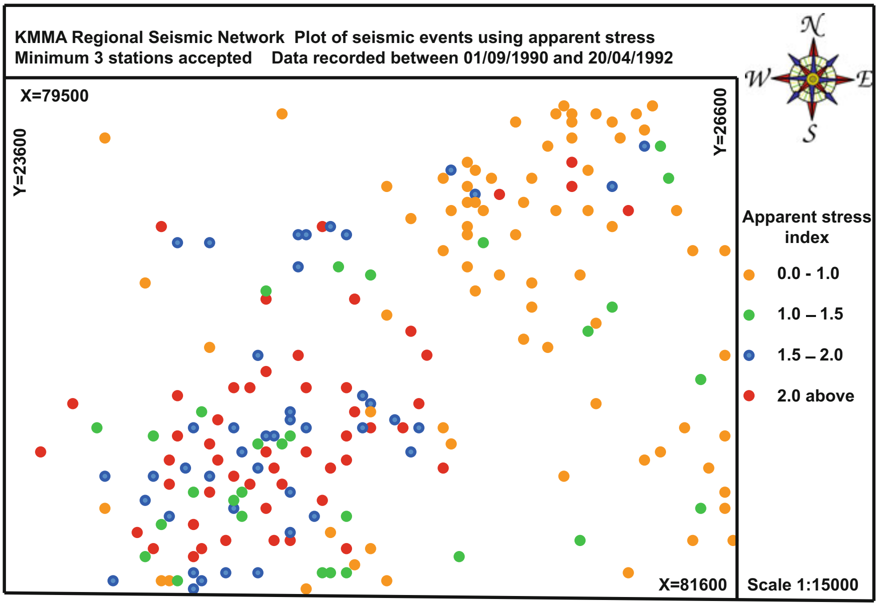


Fig. 3.31 Plot of all recorded events using their apparent stress index values

The first does not take into account changes in time, whilst the second one does. The first map for the entire region was plotted using the first approach. The entire region was divided into areas of 500 × 500 m. A time period of one year was taken into consideration. For this period of time the maximum value of the stress index for every block was found and attributed to its centre point. The next step was to draw contour lines of 1.0, 1.5, 2.0, and so on. The resulting map showed several areas that had very high values of the stress index. The Rock Mechanics personnel, as well as the mine management, at once recognized that those high value contour lines enclosed areas known to them as trouble spots. However, there were some high value contour lines at other sites that did not experience high seismicity levels, or were not known to be associated with high magnitude events in the past. We did not have to wait long, until a large event took place that closed a few hundred metres of haulage. This event was associated with an area that during a period of one year was known to have had only three small events (below 1.5 on the moment magnitude scale), but the map indicated a high value of the stress index (above 2.0).

The next step I took was to plot on this map the location and number of lost shifts and fatalities due to seismic events. There was no doubt that there was a straight forward relationship. People were injured and killed in areas where the stress index values were high. Those areas were known to be trouble spots before mapping them with the stress index. The point is that it was now possible to map them and put a value to them, based on a seismic data using physical principles and not just using the so-called “gut feeling”. It was also possible to compare those areas with each other, as the stress indices are based on a value derived for the whole region. The following step was to superimpose on this map the locations of large events—above moment magnitude 2.5. It must be pointed out that the stress index values were calculated for lower magnitude events (below 2.5). The first fact that became evident was that those big events were not associated with high values of the stress index, but rather with their high gradient values. The reason for this is that, in fact, this type of map shows boundaries between “hard” and “soft” rock, between more and less solid parts of the rock mass. The higher the apparent stress or the stress index value, the higher is the proportion of energy over deformation. A high stress index denotes more energy, while lower values of this index are associated with more deformation. This border between “energy and deformation events” forms a discontinuity which delineates the region in which those large events can take place. With more and more data available, it became possible to plot maps of this type on smaller spaced grids. In 1992, I was using a 250 × 250 m grid. Again, I was only plotting the highest value of the stress index recorded inside this base grid (from the end of 1990). An example of such a map is presented in Fig. 3.32. The red circles indicate locations of large events (above 3.0 according to the moment-magnitude value). Reading such maps, one must remember that in constructing them, a lot of averaging was involved, first by the size of the grid, and then by the contouring process itself.

Figure 3.33 illustrates the same part of the mine as in Fig. 3.32, but it is based on a grid size of 100 × 100 m. For plotting purposes, only the stress index of the latest

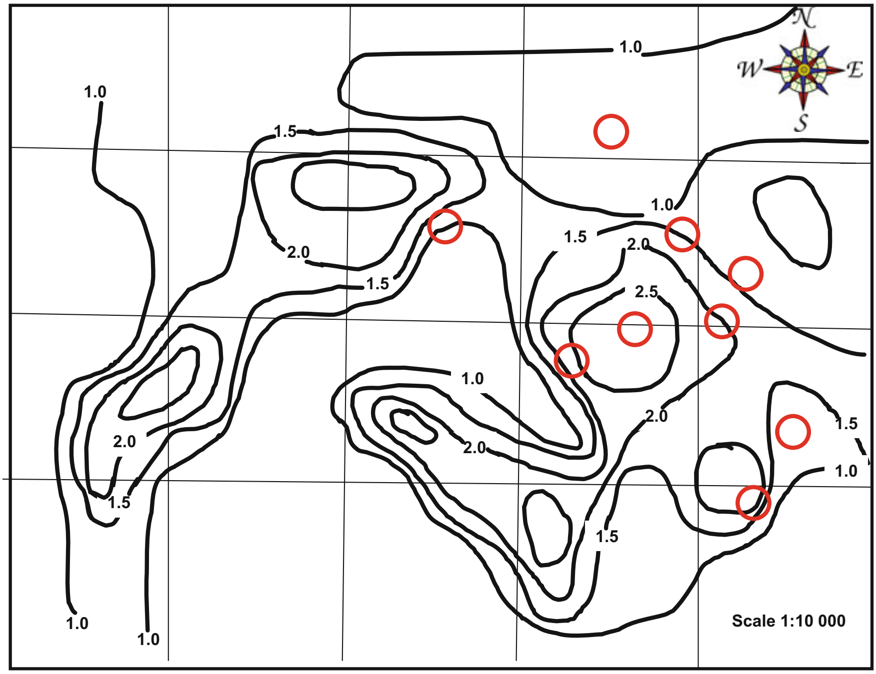


Fig. 3.32 Contours of apparent stress index with superimposed large events (grid size 250 × 250 m)

event was used, one per grid. Again the red circles indicate the locations of the big events. Their association with gradients is more evident. At that time, I was constructing these maps for the entire region every 2–3 months, using the previous map as a reference for the changes. With maps of this type, I have noticed that one can observe changes of fivefold or more in the stress index values before the occurrence of a large event. Before one of the largest events that occurred on the mine, such changes were observed close to the future source area, and were associated with relatively small events (0.0–1.0 moment magnitude). These changes took place a few weeks before the large event occurred. At the time these observations were made, it was not clear, that these changes could be attributed to a build up before a large event. Again one must remember that I made those observations using a regional network, recording small events with a limited number of stations. But as this phenomenon repeated itself constantly, one could not attribute it to an observation error. It was then planned to install some additional geophone stations, at a chosen area to test this hypothesis. With a regional network as a tool, one has to be very careful when constructing these maps. The base-grid on which they are based cannot be smaller in size than the estimated event location accuracy.

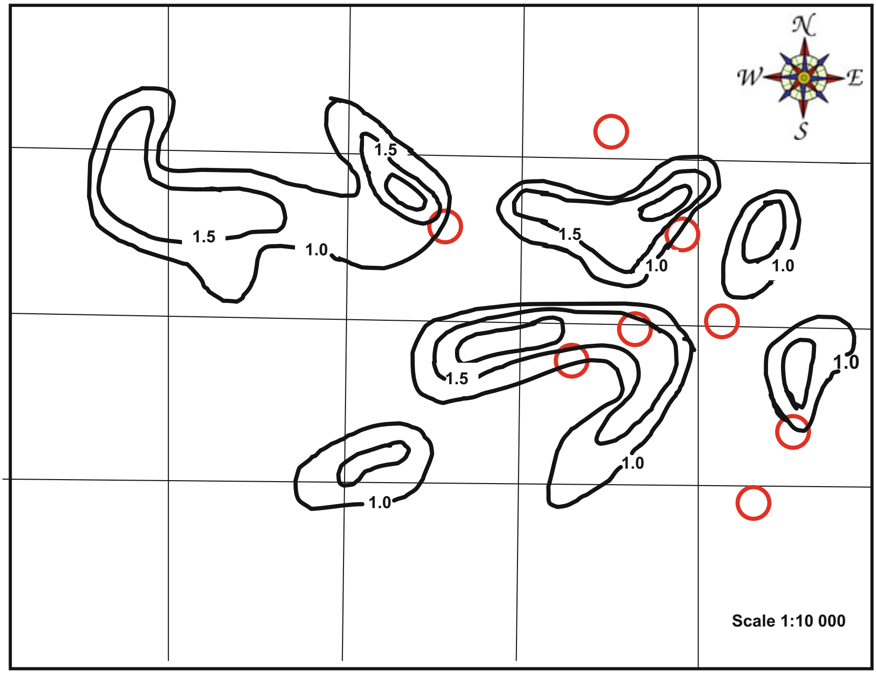


Fig. 3.33 Contours of apparent stress index with superimposed large events (grid size 100 × 100 m)

By the end of 1992, from work done to date, the following could be concluded:

1. Large events are associated with areas where there are high gradients of apparent stress index. In other words, a big event will most likely not occur where the stress index is high but constant. They are far more likely to occur where the stress index values change rapidly.
2. Before a large event will take place, it might be possible to observe changes in the values of the apparent stress index. The stress index will increase during a time span of a couple of weeks or months before a large event.
3. Damage might be experienced in areas where this parameter is high, even when the seismic source is located outside these areas. This statement is in some way controversial, as damage is a function of a number of factors (for example, the support standard or geometry).
4. The method could be used as a tool for dividing the mine into rock-burst and rock-fall areas.

It is clear that these conclusions have practical implications from the rock-mechanics and mining points of view. To make full use of the method one, will have to include into the interpretation process more seismological and other information, such as geology and mining and/or damage data. The combination of seismic, geology, and mining information should, in the end, provide more conclusive answers.

3.4 Test of the Seismic Warning Concept (End of 1993)

By the end of 1993, a significant amount of work had been done at the Klerksdorp Regional Seismic Network in order to test the instability concept. My interpretation of apparent volume is different from that presented by Mendecki (1993, 1997). Apparent volume is in fact a value that can be approximated by the square root of seismic moment weighted by the value of its apparent stress index. From this, the cumulative apparent volume is a sum of square roots of the seismic moments weighted by their apparent stress index values. For this reason, cumulative apparent volume indicates the rate of deformation, or strain in the rock-mass volume for which it is calculated. The general guidelines for qualitative interpretation of the instability criterion in the rock mass are simple. In order for a certain volume of rock mass to become unstable, the strain must increase while, at the same time, the stress has to drop. This means that there should be an increase in the rate of cumulative apparent volume, accompanied at the same time by a drop in the apparent stress index values.

Figure 3.34 indicates the location of three chosen test areas, the polygons DIKE5#, HART4 and BUFF1. The polygon DIKE5# is a block in No. 5 Shaft Vaal Reefs 140 × 400 m (56,000 m^2) in size. It is located along the Clemcor Dyke, known for its strong seismic activity. The area within the polygon has good seismic cover as there are at least 10 seismic stations in close proximity to it. The second

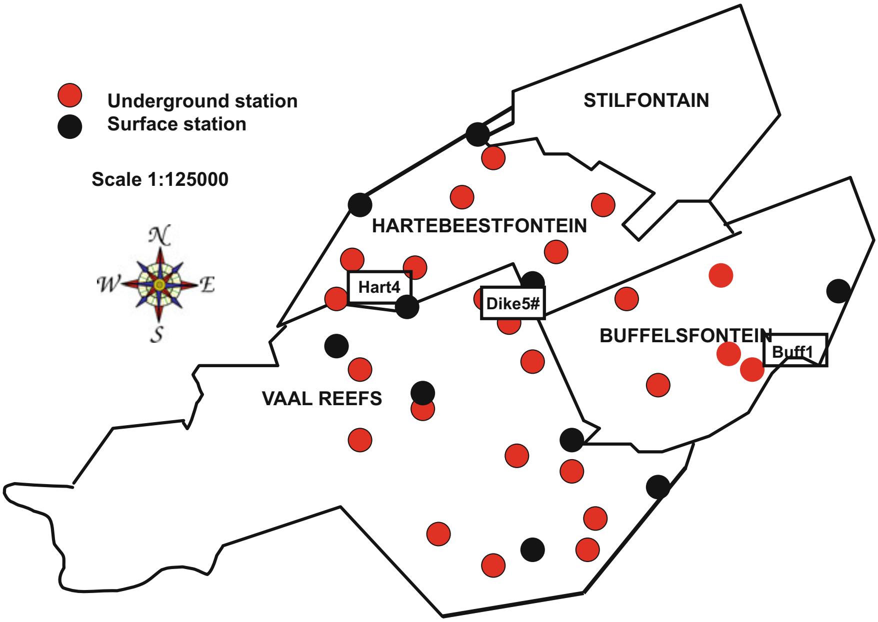


Fig. 3.34 Localization of the three test polygons

polygon HART4 is located close to No. 7 Shaft Hartebeestfontein and is 90 × 200 m (18,000 m^2) in size. This polygon is covered by two surface stations and three underground stations. The third polygon BUFF1 is located at the Southern Shaft of Buffelsfontein GM and is 300 × 300 m (90,000 m^2) in size. It is covered by one surface station and five underground stations. Seismicity used for the test was recorded between 1 January 1993 and 13 October 1993. The following numbers of seismic events were located in these polygons:

Polygon DIKE5#	241 events of which 4 were above $M_L = 2.5$
Polygon HART4	182 events of which 4 were above $M_L = 2.5$
Polygon BUFF1	194 events of which 9 were above $M_L = 2.5$

3.4.1 Results for Polygon DIKE5#

Figure 3.35 illustrates the time changes of cumulative apparent volume and the mean cumulative stress index. The software used to produce this type of plot was developed at Vaal Reefs. These two curves are presented in their smoothed version with smoothing over ten samples. This interpolation procedure was introduced to compensate for two factors: first, not enough data (on average less than one event per day) and, second, the events were not spread equally over time. The time occurrence of events of magnitude above $M_L = 2.5$ is indicated (in scale). There is

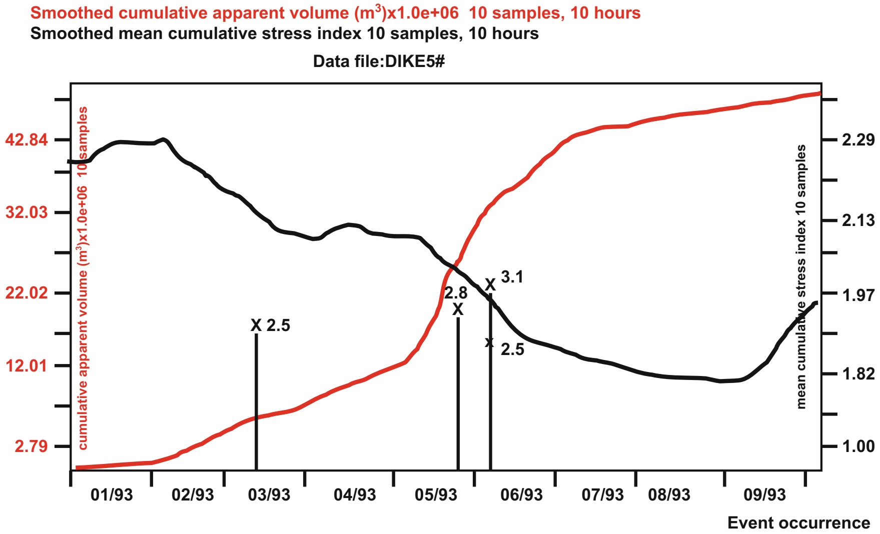


Fig. 3.35 Time variations of cumulative apparent volume and mean cumulative apparent stress index (all events)

a significant drop in cumulative stress index (black curve) about one month before the M_L = 2.5 event in March 1993 and a similar drop also about a month before the M_L = 2.8 event at the end of May 1993 and the two events M_L = 3.1 and M_L = 2.5 at the beginning of June 1993. The curve of cumulative apparent volume (red curve) shows an increase in its gradient about two weeks before the events in May and June 1993. No such change can be seen before the event of March 1993.

Figure 3.36 illustrates time changes of cumulative apparent volume and the mean cumulative stress index. This time, the curves are based only on values derived from those events that were lower than M_L = 1.0. The same smoothing and interpolation filters were used as in case of data presented by Fig. 3.35. The shapes of the curves as presented by Fig. 3.36 are the same as those of Fig. 3.35. The only difference is the values on the vertical axis. Here they are lower, which is logical, as all big events are removed. In order to get some qualitative values for the variations observed in Figs. 3.35 or 3.36, the derivative of the cumulative apparent volume (black curve) is plotted together with the cumulative apparent-volume curve (red) itself (Fig. 3.37).

Figure 3.38 presents the same curves, as in Fig. 3.37 but only for events lower than M_L = 1.0 in order to get rid of the influence of big events on the final results.

The similarity between the two figures is evident. The two derivative curves match each other not only in their shape, but also in their absolute values. In these two figures, there is the same value of about 0.8 for the derivative of the cumulative apparent volume 15 days before the major events that took place between 26 May 1993 and 05 June 1993.

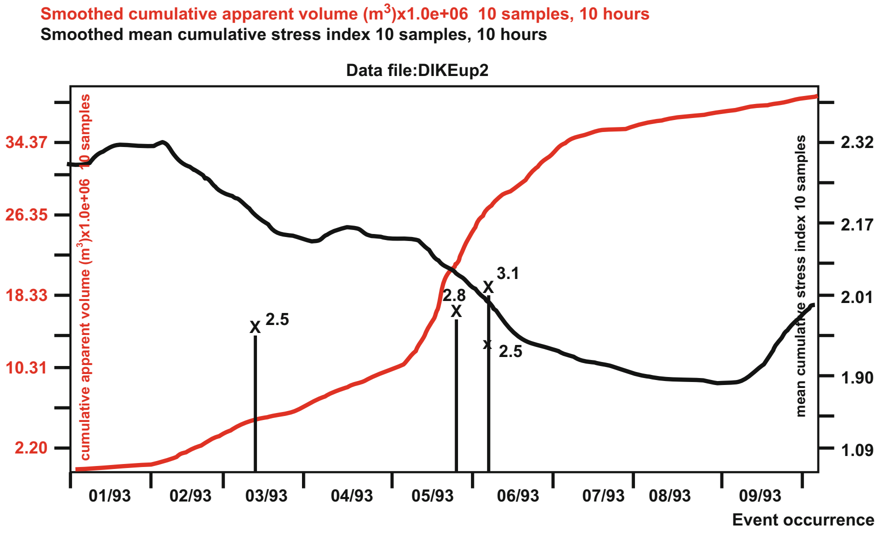


Fig. 3.36 Time variations of cumulative apparent volume and mean cumulative apparent stress index (events of magnitude below 1.0)

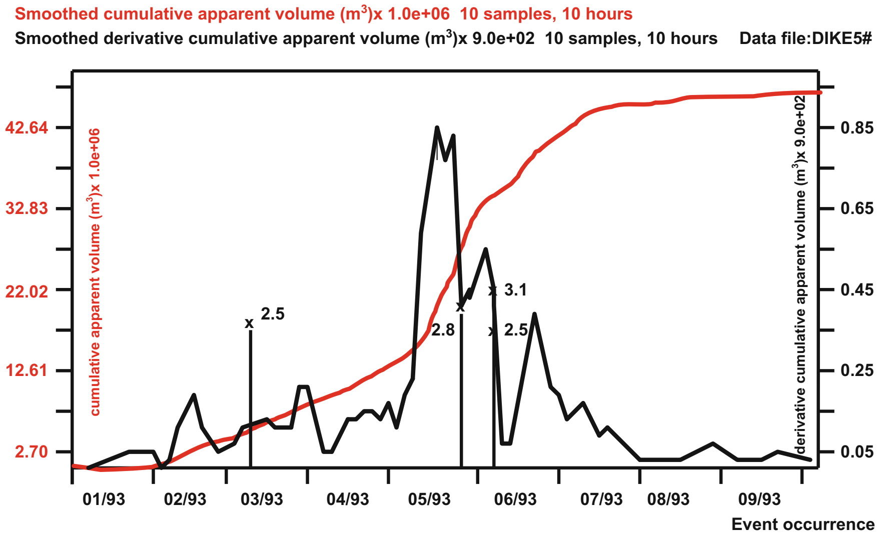


Fig. 3.37 Time variations of the cumulative apparent volume derivative together with the curve of cumulative apparent volume (all events)

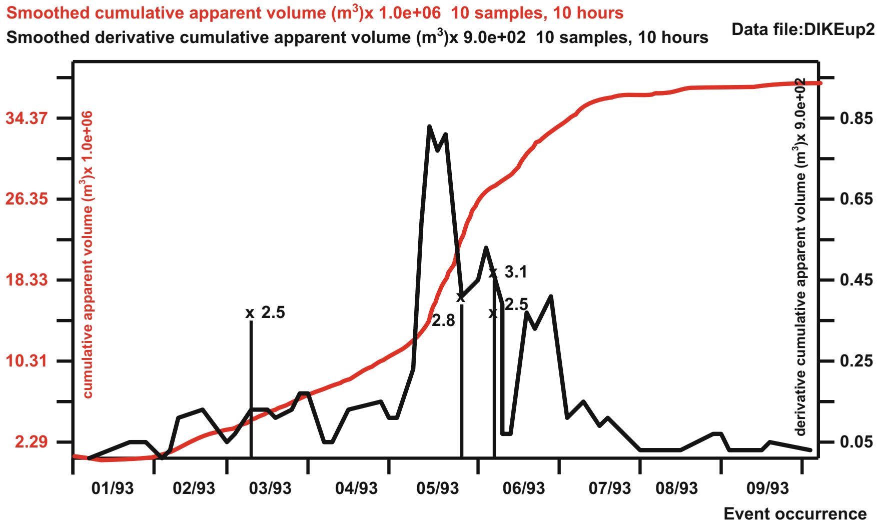


Fig. 3.38 Time variations of the cumulative apparent volume derivative together with the curve of cumulative apparent volume (events of magnitude below 1.0)

3.4.2 *Results for Polygon HART4*

A similar analysis was done for polygon HART4, using the same filters for interpolation and smoothing. A linear interpolation function with a time interval of ten hours and ten samples in the interpolation domain are then used to smooth the function. Figure 3.39 depicts the time variations of the cumulative apparent volume and the mean cumulative-stress index (all events taken into account).

Figure 3.40 presents the time variations of cumulative apparent volume and mean cumulative stress index (only for events up to $M_L = 1.0$). Figure 3.41 shows the time variations of the cumulative apparent volume derivative plotted together with the curve of cumulative apparent volume.

Figure 3.42 shows the time changes of the derivative of the cumulative apparent volume plotted together with the curve of cumulative apparent volume for events of local magnitude up to $M_L = 1.0$.

Figure 3.42 shows the time changes of the derivative of the cumulative apparent volume plotted together with the curve of cumulative apparent volume for events of local magnitude up to $M_L = 1.0$. From the last four graphs, the following can be concluded:

1. The cumulative stress index increases prior to the occurrence of big events (from January 1993 to mid-April 1993).
2. The cumulative stress index drops after big events have occurred (mid-April 1993 to the end of July 1993).

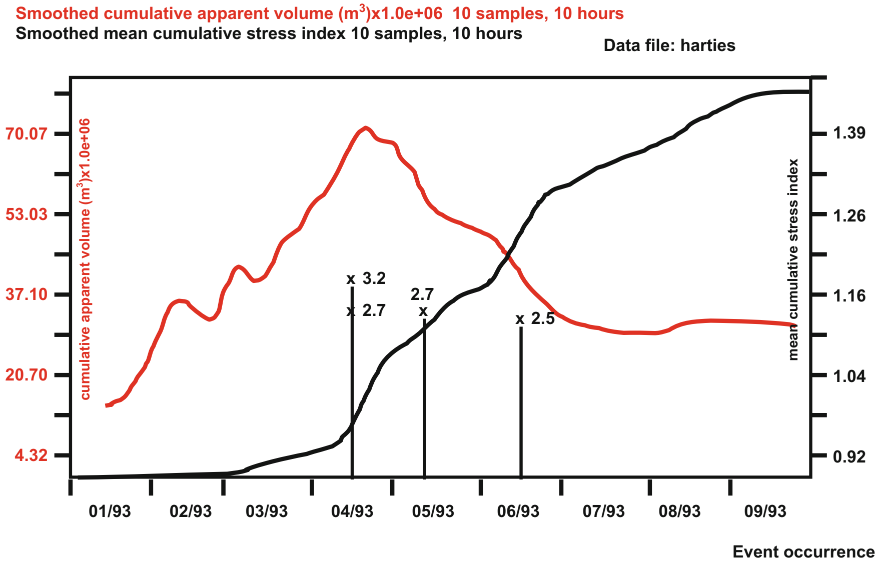


Fig. 3.39 Time variations of cumulative apparent volume and mean cumulative apparent stress index (all events)

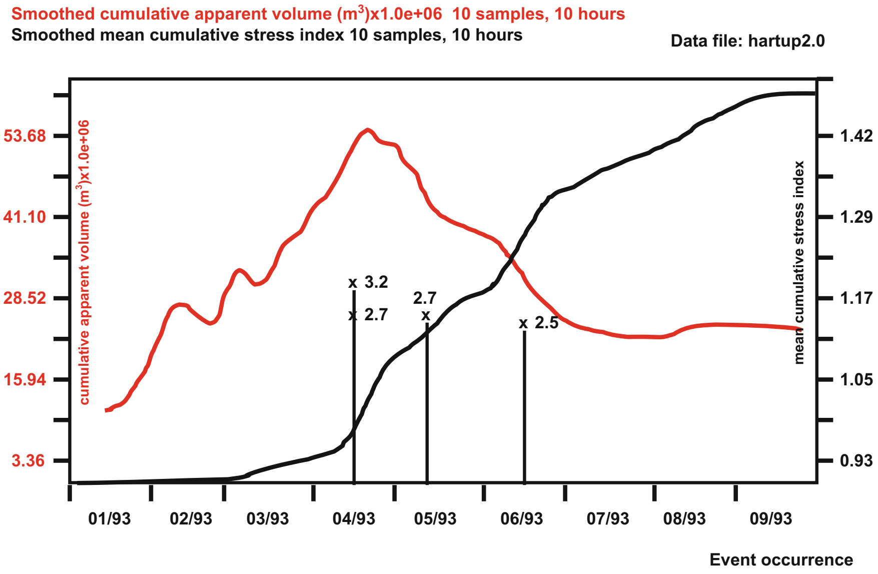


Fig. 3.40 Time variations of cumulative apparent volume and mean cumulative apparent stress index (events of magnitude below 1.0)

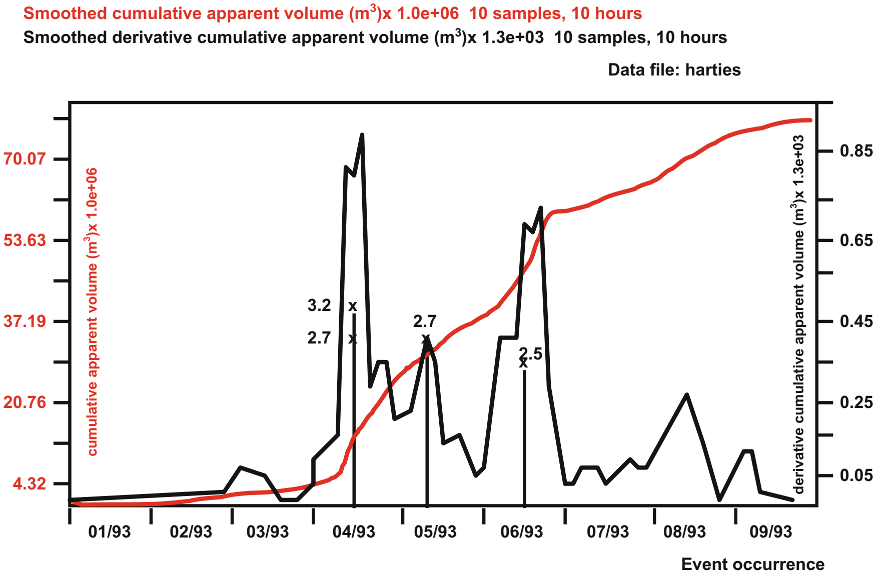


Fig. 3.41 Time variations of the cumulative apparent volume derivative together with the curve of cumulative apparent volume (all events)

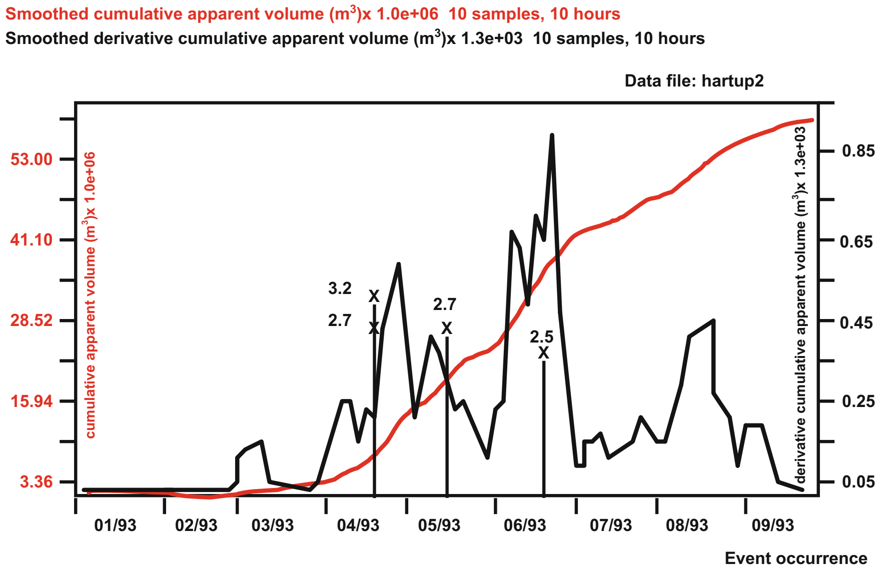


Fig. 3.42 Time variations of the cumulative apparent volume derivative together with the curve of cumulative apparent volume (events of magnitude below 1.0)

3. The cumulative stress index has a constant value after the big events have taken place, from July 1993 to the end of the test period.
4. There is a distinctive change in the slope of cumulative apparent volume before the first two major events of $M_L = 3.2$ and $M_L = 2.7$ in April 1993. This slope stays constant until the next two events take place (first $M_L = 2.7$ in May 1993 and then $M_L = 2.5$ in June 1993). From the end of May 1993 to the end of the test period (end of September 1993), the slope of cumulative apparent volume drops.

The cumulative apparent volume derivatives (Figs. 3.41 and 3.42) are similar in shape but not in their absolute values. This is due to the fact that, in the case of this polygon, there are not many events below $M_L = 1.0$ as is the case for polygon DIKE5#. Even so, there is an increase in the derivative value three to five days before the occurrence of major events that took place on the 14 April 1993, on the 10 May 1993, and on the 16 June 1993.

3.4.3 Results for Polygon BUFF1

A similar analysis was done for this polygon as for the previous two, using the same filters for interpolation and smoothing. A linear interpolation function with a time interval of ten hours and ten samples in the interpolation domain were then used to

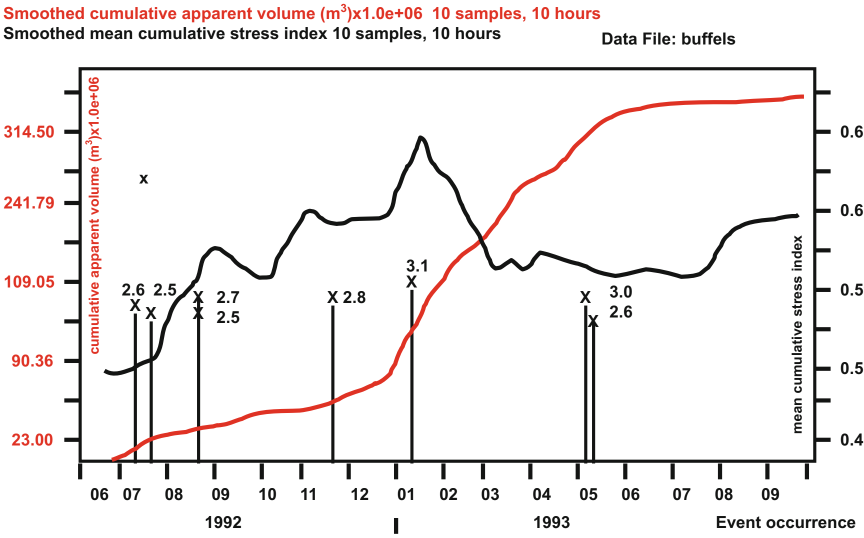


Fig. 3.43 Time variations of cumulative apparent volume and mean cumulative apparent stress index (all events)

smooth the function. Figure 3.43 shows the time variations of cumulative apparent volume and mean cumulative stress index (all events taken into account).

Figure 3.44 shows the time variations of cumulative apparent volume and mean cumulative stress index only for events up to $M_L = 1.0$.

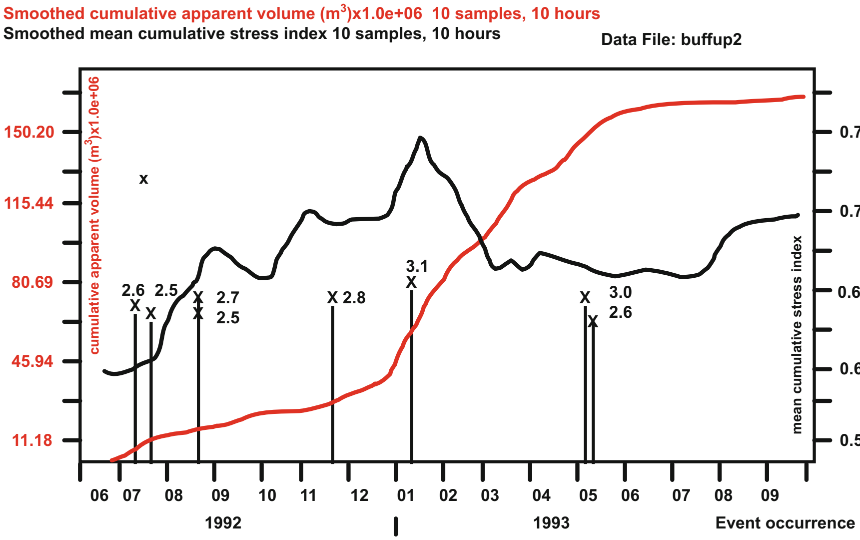


Fig. 3.44 Time variations of cumulative apparent volume and mean cumulative apparent stress index (events of magnitude below 1.0)

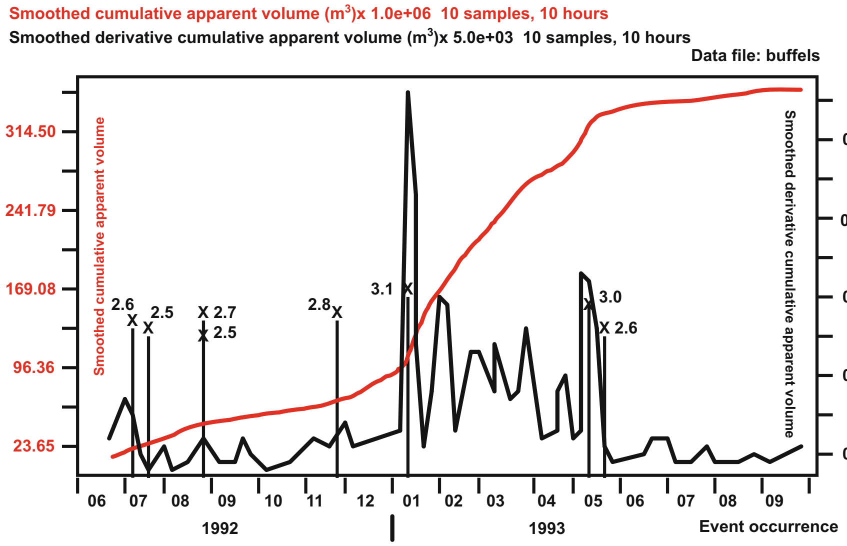


Fig. 3.45 Time variations of the cumulative apparent volume derivative together with the curve of cumulative apparent volume (all events)

Figure 3.45 shows the time variations of the cumulative apparent volume derivative plotted together with the curve of cumulative apparent volume itself (for all events).

Figure 3.46 shows the time variations of the cumulative apparent volume derivative plotted together with the curve of cumulative apparent volume itself, only for events below $M_L = 1.0$.

From the last four figures, the following can be concluded:

1. The cumulative stress index increases significantly only before the occurrence of the event of $M_L = 3.1$ that took place at the beginning of January 1993.
2. The slope of the cumulative apparent volume changes dramatically only a couple of days before the $M_L = 3.1$ at the beginning of 1993, and the slope drops only after the occurrence of the two events of May 1993 ($M_L = 3.0$ and $M_L = 2.8$).
3. There is no precursory behaviour that can be attributed to the events that took place in July, August, and November 1992.
4. The derivatives of the cumulative apparent volume (Figs. 3.45 and 3.46) are similar in shape but not in their absolute values. From these two figures, one can see a distinct increase in absolute values three to five days before the occurrence of major events.

   $M_L = 3.1$ on the 6 January 1993 and the two $M_L = 3.0$ and $M_L = 2.6$ that occurred between 3 May 1993 and 6 May 1993.

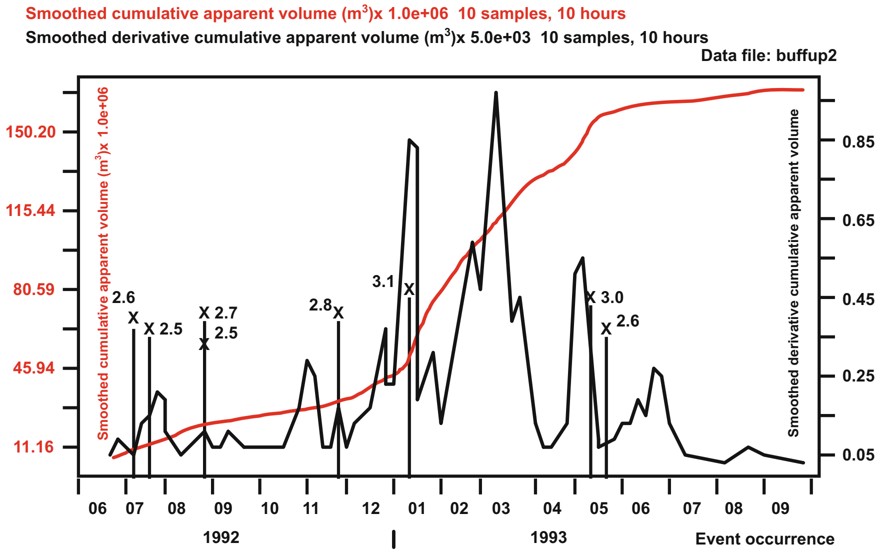


Fig. 3.46 Time variations of the cumulative apparent volume derivative together with the curve of cumulative apparent volume) (events of magnitude below 1.0)

The changes of the derivative of the cumulative apparent volume for the events taking place from July 1992 and November 1992 are too small to define them as precursory.

3.4.4 *Summary of the Test*

This test summarizes about two years of work done on the development of interpretation methodology and the PC-based software supporting this type of seismic data interpretation. In this test, the apparent stress index was tested to find out if it can be used to monitor changes that could then indicate that a large-sized event might take place. The second parameter tested at the Klerksdorp Regional Seismic Network was the cumulative apparent volume. Primarily, it was used for testing the dyke de-stressed volume size after the occurrence of a large seismic event (see Sect. 3.3.2). Application of cumulative apparent volume for this test was taken from Mendecki (1993) and van Aswegen and Butler (1993). In summary, this test indicated that:

1. There is definite merit in the instability concept.
2. The cumulative apparent volume and the cumulative apparent stress index show significant changes in their shapes and their values before the occurrence of a big event.

3. Those changes can manifest themselves in the days or weeks before the event takes place.
4. Those changes can be observed also when only small events ($M_L \leq 1.0$) are analyzed.

The amount of data that is used for interpretation purposes is important. The more events available, the more significant and clear the changes are. To compensate for the number of events and their distribution, an interpolation technique was applied, but this must also have its practical limitation due to the number of events. It is unclear how to determine the place where the event will take place. It is probably due to the polygon size, its shape or volume that not all large events located in the test areas (DIKE, HART, BUFF) manifested themselves by changes in the shapes and absolute values of the curves.

3.5 Future Strategy for Seismic Monitoring at Vaal Reefs Based on 1993 Knowledge

Since 1972, Vaal Reefs had participated in monitoring seismicity through the Klerksdorp Regional Seismic Network. At the end of 1988, Vaal Reefs employed for the first time a qualified seismologist in order to advise mine management on developments in the field of mine seismology. By the beginning of 1989, it became clear that the existing network suffers the basic limitation of analogue transmission, not only due to the high ratio of noise to signal and low dynamic range, but also because of it not being calibrated. The system was recognised as being obsolete and recommendations were made to replace it with a modern digital one. This resulted in a major upgrade of the Klerksdorp Regional Seismic Network by the end of 1990. Every year, seismic events injured, killed workers and disrupted production. The number of events above $M_L = 3.0$ that are usually associated with injuries and fatalities fluctuate around five events per month for the period 1990–1993. Those facts made the prevention problem very urgent. For this reason, the Vaal Reefs Seismic Project was created at the end of 1992. It was there to create manpower and financial resources that should have resulted in more active and practical prevention actions. New seismological concepts of interpreting seismic data were developed and tested, but this had its limitations mainly due to the network configuration. Those concepts required more input data which in practice means better seismic cover. The new interpretation methods required the installation of new geophone stations. By the end of 1990, the network consisted of 32 geophone stations of which only 15 (47%) were located at Vaal Reefs. By the end of 1993, there were already 42 geophone stations in the network of which 25 (60%) were located at Vaal Reefs. By the end of 1993 it was recognised that the Regional Seismic Network had reached its limit, as it could not provide sufficient cover, if the interpretation methods that were developed were to be applied in practice as a matter of routine. For this reason, a plan for further development of the seismic monitoring facilities had to be prepared and then implemented. This last would require substantial capital financing. Three options for the implementation of the seismic monitoring strategy had to be investigated. Those options were:

- Centralisation of the networks
- De-centralisation of the networks
- Centrally controlled de-centralised networks.

By the beginning of 1994, a five-year seismic monitoring strategy for Vaal Reefs was formulated. This five-year plan of seismic monitoring and application of seismic information at Vaal Reefs was divided into two phases: the short term plan for 1994–1995 and the long term plan for 1996–1998. This plan took into account two levels of Vaal Reefs involvement in seismic monitoring. The first was through the Regional Seismic Network because of Vaal Reefs commitment to provide seismic cover for Buffelsfontein and Hartebeestfontein Gold Mines. The second level was through Vaal Reefs Seismic Project which considered only for internal Vaal Reefs requirements. This strategy was based on actual technical realities and knowledge as far as the short-term plan was concerned. It took into consideration expected changes in technology and science for the long term plan.

The short term plan for 1994–1995 included the following:

(A) For 1994:

1. Test of the energy index concept at the 5B area of No. 5 Shaft Vaal Reefs by installing a sub-network in this area consisting of eight geophone stations.

(B) For 1995:

1. Introduction of the energy index concept at 5B area of No. 5 Shaft Vaal Reefs as a practical tool to manage the rock burs hazard
2. Making a decision about the future seismic-monitoring development strategy for Vaal Reefs
3. Installation of a shaft pillar network at No. 5 Shaft Vaal Reefs
4. Partial upgrade of the Regional Seismic Network recording stations with new technology.

The long term plan 1996–1998 included the following:

(A) For 1996:

1. Implementation of the best option for seismic monitoring
2. Implementation of the instability concept at several underground working places in rock-burst conditions, as a management tool to control seismicity
3. Completion of the upgrade to the Klerksdorp Regional Seismic Network.

(B) For 1997–1998:

1. Completion of the implementation of the energy-index concept at all underground working areas that experience rock burst conditions
2. Immediate implementation of any new developments in applied mine seismology that could result in active combating of rock-burst hazard.

3.6 Summary and Conclusions

This chapter describes what was done in mine seismology from 1990 to 1993. The start date is the time when the KMMA Regional Seismic Network was upgraded to digital technology. During the experimental time up to 1993, new methodology for using the recorded seismicity for analysis and interpretation was developed. During this experimental time, new recording outstations were added to the regional network. Seismic analysis and interpretation was used in several cases that were of practical impact for the mine management. Such an example was the case when recorded seismicity was used after a large event that was located at the dyke to decide if the dyke is unstressed and if it is safe to continue with the underground work. A second such case was the use of seismicity to compare an area employing different support, namely backfill, and that with elongates and packs. Recorded data indicated that, in this case, the expensive backfill did not influence the seismicity. For this reason, it was decided to stop the backfill and implement much less expensive support. This was the second case where seismic information was used to reduce the costs of the support and, at the same time, not reduce safety. The first case of a similar application of recorded seismicity is described in Sect. 2.6. This test time included several back analyses of recorded large-sized seismicity. In most cases, this back analysis consisted of two parts. It was important to analyse the seismicity recorded before this event with that recorded after it took place. Another example was the use maps of the index, instead of maps with recorded seismicity presented by its magnitude values. This type of analysis enabled connecting underground damage with stress conditions. It also explained why certain areas with smaller-sized seismicity experienced more underground damage compared with that where the seismicity was of larger magnitude. A lot was learned from this type of analysis. For example, at the time it was expected that recorded seismicity would enable division of the mine into rock-fall and rock-burst areas. This would help with support strategy. By the end of 1993, not only the mine seismologist but also the mine management understood the need for recording small-sized seismicity. These small events were supplying information about the rock mass from which they originated. These were the fortunate events as opposed to those that resulted in damage. Probably for the first time in the history of South African gold mining, a plan for implementation of shaft networks was done at the mine itself. There was no influence from outside in the planned strategy. The mine managers were interested in further development of seismology at their mines.

References

Adams DJ, Hemp DA, Spottiswoode SM (1990) Ground motions in a backfield stope during seismic events In: Brummer RK (ed) Proceedings of static and dynamic considerations in rock engineering, Balkema, Rotterdam, pp 13–22

Butler AG (1997) Application of weighted energy index for routine evaluation of rockburst potential. In: Gibowicz SJ, Lasocki S (eds) Proceedings of 4th international symposium on rockburst and seismicity in mines. Crakow, Poland, 11–124, Aug 1997, pp 317–323

Gibowicz SJ, Harjes HP, Schäfer M (1990) Source parameters of seismic events at Heinrich Robert Mine, Ruhr Basin, Federal Republic of Germany: evidence of nondouble-couple events. Bull Seismol Soc Am 80:88–109

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

Gibowicz SJ, Young RP, Talebi S, Rawlence DJ (1991) Source parameters of seismic events at the Underground Research Laboratory in Manitoba, Canada: scaling relations for the events with moment magnitude smaller than −2. Bull Seismol Soc Am 81:1157–1182

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

Hemp DA, Goldbach O (1993) The effect of backfill on ground motion in a stope during seismic events. In: Young RP (ed) Rockburst and seismicity in mines. Balkema, Rotterdam, pp 75–79

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 Seismol 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

Mendecki AJ (1993) Keynote address: real time quantitative seismology in mines. In: Young RP (ed) Rockburst and seismicity in mines. Balkema, Rotterdam, pp 287–296

Mendecki AJ (ed) (1997) Seismic monitoring in mines. Chapman and Hall, London

Snoke JA (1987) Stable determination of (Brune) stress drop. Bull Seismol Soc Am 77:530–538

Snoke JA, Linde AT, Sacks IS (1983) Apparent stress: an estimate of the stress drop. Bull Seismol Soc Am 73:339–348

Spottiswoode SM, Churcher JM (1988) The effect of backfill on the transmission of seismic energy. In: Proceedings of backfill in South African mines. Southern African Institute of Mining and Metallurgy, Johannesburg, pp 203–217

van Aswegen G, Butler AG (1993) Applications of quantitative seismology in South African gold mines. In: Young RP (ed) Rockbursts and seismicity in mines. Balkema, Rotterdam, pp 261–266

Wyss M, Brune JN (1968) Seismic moment, stress and source dimensions for earthquakes in the California-Nevada region. J Geophys Res 73:4681–4694

Chapter 4
No. 5 Shaft Experiment with Seismic Warning

Testing of the seismic warning concept at No. 5 Shaft Vaal Reefs took 17 months. Those 17 months started at the end of December 1994 and concluded in May 1996. It is important to understand that at that time no one, starting from the mine seismologists through rock engineering staff and up to the mine management and decision-making, high-ranking management, was expecting that warnings could predict the events, in the sense that their place, time, and size would be know before they took place. From the beginning of the experiment, this was well understood. Prediction terminology was used to start with since no one was exactly sure how to name what was happening. The phrase “Alert/Alarm” was also in use but, over time, the “seismic warning” expression was developed and accepted.

The short term plan included testing of the warning concept in a selected area during 1994 and then implementing this concept, as a practical working tool for managing seismicity during 1995. This also meant establishing a procedure for handling this type of information by rock engineering and mining personnel. In parallel, work was done to establish the best option for Vaal Reefs regarding the expansion of its seismic monitoring facilities. Apart from the technical and financial aspects, this study included the manpower requirements. The short-term plan made provision for the installation of a mini-network in one of the shaft pillars that was planned for extraction. By end of 1995, most of this plan was already completed. An experimental sub-network consisting of eight geophone stations was fully operational beginning September 1994. This network was located at the centre of the regional network at No. 5 Shaft as illustrated in Fig. 4.1.

The first seismic warning was issued on 8 October 1994, and an event occurred in the expected area three days later. By February 1995, a procedure for handling seismic warnings was approved by mine management and put into practice. This procedure described preventive actions that had to be taken in all working places, under seismic-warning conditions. It also identified the persons responsible for introducing them and described the control procedures. By the end of 1995, Vaal Reefs had already established a clear concept for a seismic-monitoring strategy. This was a concept based on one central site, serving all Vaal Reefs shafts and

S.N. Glazer, *Mine Seismology: Seismic Warning Concept*,
https://doi.org/10.1007/978-3-319-62353-5_4

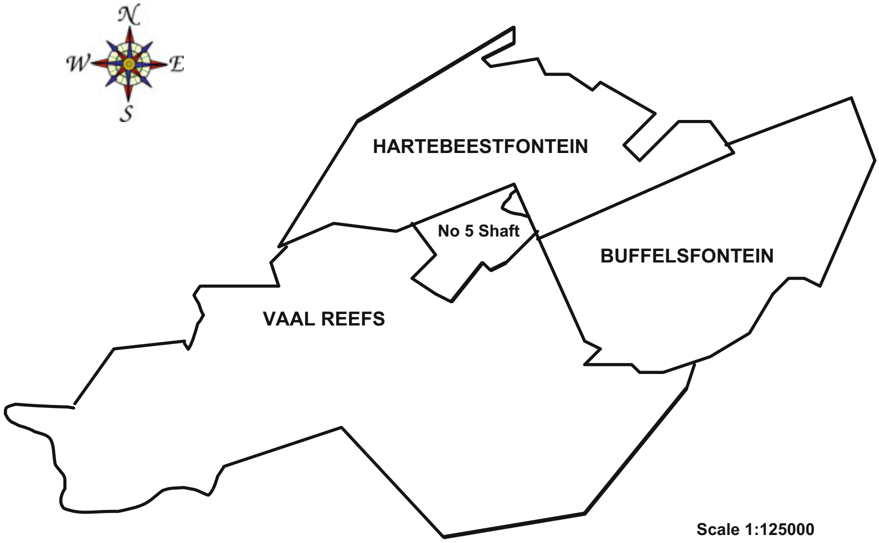


Fig. 4.1 Experimental sub-network 5B area at No. 5 Shaft Vaal Reefs

mines, connecting all sub-networks and networks together. Consequently, the central site was rebuilt and equipped with new computerized technology. A decision was made to increase the size of the seismic staff. From June 1994, the seismic central site was to be staffed 24 h a day on a three-shift basis. This resulted in an improved quality of recorded seismic data, but, more importantly, all events of damaging potential were immediately reported to the shafts. This enabled them to send proto teams, without delay, straight to the affected areas. The first Shaft Pillar Network became fully operational in October 1995.

Implementation of the long-term plan for 1996–1998, as decided in 1994, was based on results of actions taken in 1994–1995. The major factors were the results of implementing the instability or warning concept in the test area. For the period December 1994 to the end of May 1996, the network recorded 77 potentially damaging events, of which 62 were predicted. This was a success rate of 80%. There were two factors that should be noted. The first was connected with the warning success-rate itself. During this period, the success rate increased from month to month, indicating that the instability concept was being implemented in the correct manner. The next was that Vaal Reefs adopted the philosophy that the success rate should be measured in preventive actions taken, rather than in the success of the prediction itself. Several preventive actions were put into practice that included additional safety pillars, changes in mining sequences and directions, and also a review of the mining strategy for the whole 5B area. The long-term seismic strategy, as formulated at the beginning of 1994 postulated, that, by the end of 1996, the best option for seismic monitoring should be implemented and that all seismically active working places should have in place sufficient cover for implementing the instability concept. This was directly related to the density of the geophone monitoring stations. By the end of 1998, this concept should be in place in most of the seismically active working places. By June 1996, the above plan was completed. The implementation of centrally controlled networks and sub-networks was completed by the end of 1995. Section 5.3 presents a technical description of the Klerksdorp Regional Seismic Network central side. Appendix 5.1 provides technical descriptions of all the seismic networks in the Klerksdorp area as they were at the end of 1997. Funds for increasing the number of seismic stations from 46 to 130 had been made available, and more capital for an additional modernization of the central site was granted.

4.1 Assumptions Behind the Seismic-Warning Concept

If it would be possible to monitor the relationship between stress and strain for a given rock-mass volume, then it could be possible to estimate whether it is stable or not. The stress of the rock mass is indicated by the value of the apparent stress index or energy index (which conceptually is the same as apparent stress index), which normalizes the seismic energy over a wide range of the seismic-moment values. The index itself is calculated as the ratio between the measured and the mean values. The latter is given by a regression line derived from all recorded events. In this way, values above 1.0 indicate higher stress levels than average, while values below 1.0 indicate stress lower than the average. At the time, it was assumed that the cumulative apparent volume indicates the rate of deformation, or strain in the rock-mass volume for which it is calculated (Mendecki 1997). Seismic parameters, such as seismic energy or seismic moment, do not measure the actual stress, or strain, but are related to them. The higher the energy index, the higher is the stress. The steeper the slope of the cumulative apparent volume curve, the higher the strain-release rate. A seismic warning could be issued when there would be an increase in strain and a simultaneous decrease in the stress. With regard to time histories, this would be when the energy-index values decreases with time, while at the same time the slope of the cumulative apparent volume increases. This was tested and already presented in Sect. 3.4.

4.2 The First Seismic Warnings (October–December 1994)

After installation of a sub-network of eight stations at the 5B area, the Klerksdorp Regional Seismic Network started to record an increased number of small events. Data presented in Table 4.1 was taken from the networks' monthly report for November 1994. It shows the number of seismic events recorded by the KMMA Regional Seismic Network from January 1994 to the end of November 1994.

Table 4.1 Numbers of seismic events recorded by the KMMA Regional Seismic Network

Month	Magnitude range					
	<0.9	1.0–1.9	2.0–2.9	3.0–3.9	4.0–5.2	Total
January 94	461	197	66	10	0	734
February 94	653	205	49	5	0	912
March 94	621	240	51	5	0	917
April 94	593	188	48	4	1	834
May 94	541	215	68	8	0	832
June 94	531	221	61	13	0	826
July 94	548	229	68	8	0	853
August 94	758	233	61	3	0	1055
September 94	980	205	50	8	0	1243
October 94	1216	202	66	11	0	1495
November 94	1243	204	51	10	0	1508

The seismic-warning concept was applied by the mid-October 1994. Several areas of interest were selected by the seismologist and the rock engineer who was responsible for the region at that time. One of those polygons 'TRIBUTE', named offer the Tribute Dyke, was 400 × 200 m in size and was selected for continuous monitoring due to clearly visible space clusters of seismic events and a concentration of underground working places. The next three figures show, for the selected volume of polygon 'TRIBUTE', the observed changes in the curves of cumulative apparent volume which indicate strain changes and changes in the curves of the stress index that represent changes in stress. For this polygon, an unofficial seismic warning, which was only for the rock engineering staff, was released on 10 October. Figure 4.2 illustrates the seismic time history for 120 days. During those four months, 117 events were recorded inside this polygon. This warning was based on the similarity in trends that can be observed for the event of $\log_{10}E = 7.41$ ($M_L = 2.0$) of 22 September and those for the 10 October. The blue curve represents the cumulative apparent volume (strain), while the red curve represents stress index (stress). In both cases, there are visible increases in the strain rate accompanied by a drop in stress. On these plots, all the events for which $\log_{10}E$ is above 7.0 are indicated by arrows at the top of the plot ($\log_{10}E = 7.0$ means that $M_L = 1.9$, $\log_{10}E = 9.71$ means that $M_L = 3.5$ and $\log_{10}E = 7.41$ means that $M_L = 2.0$).

Figure 4.3 illustrates the situation just before the event of 12 October of $M_L = 2.0$ ($\log_{10}E = 7.15$). The increase in strain rate is even more visible, as is the stress drop. There is also an increase in the level of seismicity. Figure 4.4 illustrates the situation a couple of days after the event took place. There is a drop in strain rate and an increase in stress.

During the next two months, seven similar observations of this type were made, and unofficial warnings were given only for the information of the rock engineering staff and the shaft manager. By the end of December 1994, 13 different polygons

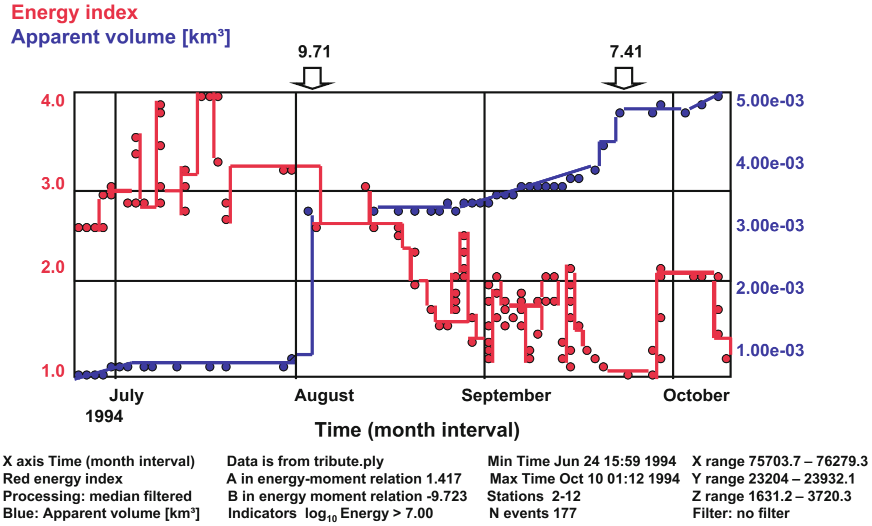


Fig. 4.2 TRIBUTE Cumulative apparent volume and the stress index (10 October 1994)

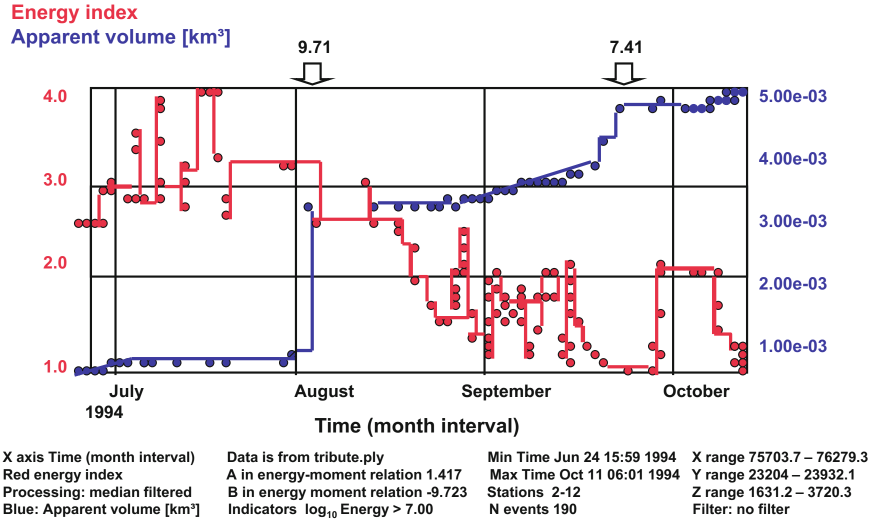


Fig. 4.3 TRIBUTE Cumulative apparent volume and the stress index (11 October 1994)

were continuously monitored. The shape and size of those polygons were changed very often in order to test trends for various data sets. On 28 December 1994, the first official warning was issued, this time also for the information of the No. 5 Shaft management (Prinsloo et al. 1995). The polygon for which this warning was issued was 200 × 150 m in size. The seismic event then occurred on 31 December 1994 at

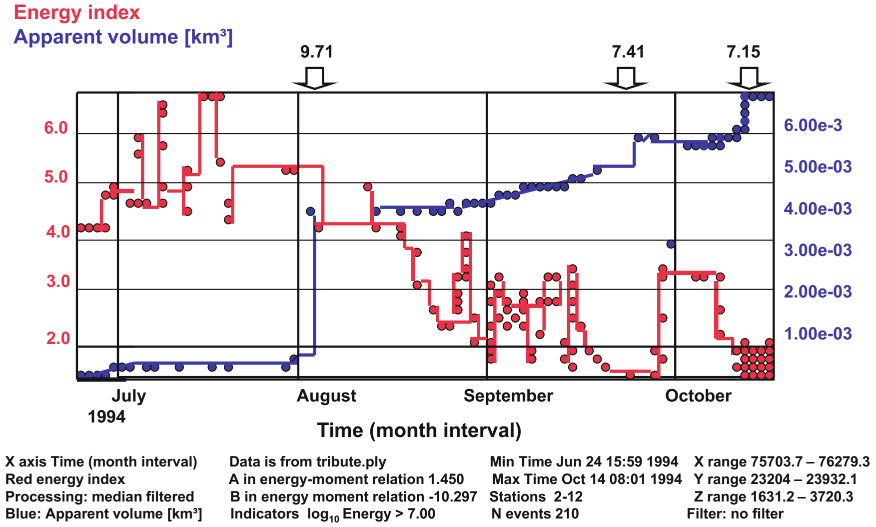


Fig. 4.4 TRIBUTE Cumulative apparent volume and stress index (14 October 1994)

15:27 and was of local magnitude 3.4 (Appendix 4.1, position 1). This appendix is placed at the end of this chapter. The event was located in the centre of the polygon. This warning was issued on the basis of the energy-index curve as shown in Fig. 4.5, unfortunately not in the form as shown in Fig. 4.6. The shape of the softening curve shown in Fig. 4.6 was only produced after testing different filtering

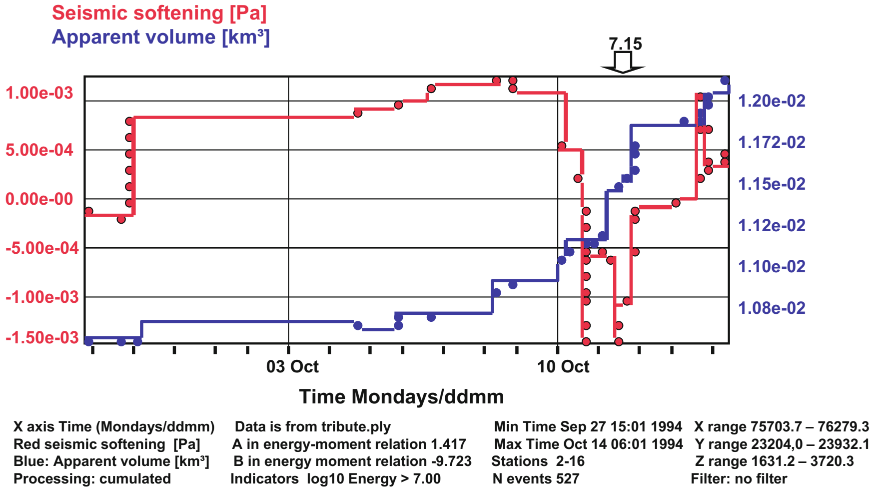


Fig. 4.5 Energy index time history that was the base of the first seismic warning (28 December 1994)

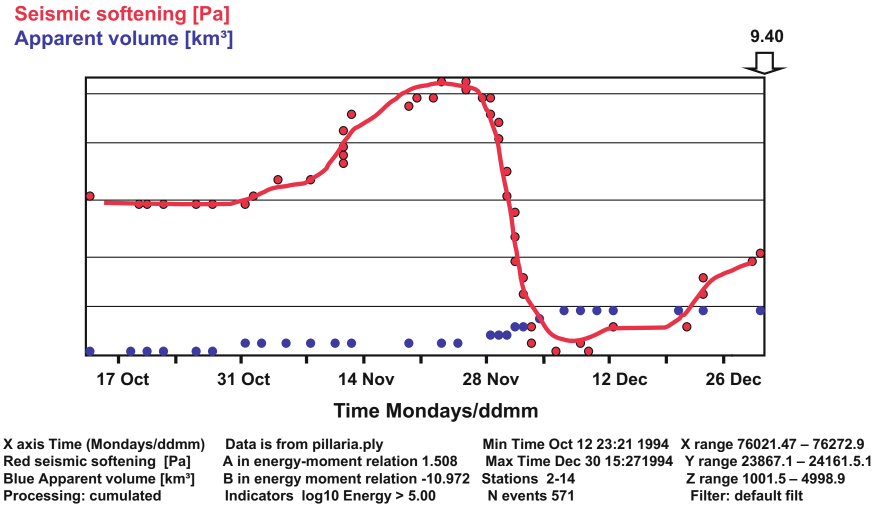


Fig. 4.6 Energy-index time history shape after back analysis (first seismic warning)

techniques after the event had already taken place. According to this figure, this event could have been predicted one month before it took place—the softening curve goes into negative values on 1 December 1994—and not only two days before, as was the actual case. This indicates that interpretation of this type of data is very sensitive, not only to the input, but also to the way it is then manipulated (smoothed). By the end of the year, I made a presentation to the mine inspectors. When I presented some data from the experiment, they got really exited that now the mine had a tool to protect miners from the effects of seismicity. What's more, from now on they were ready to be very critical of the mine management in cases of a seismic-related accident. This attitude indicated that they did not understand the idea of seismic warning. I had to do something quickly in order to avoid certain trouble in future. I showed them how the trends of the index changes with changing the smoothing parameters or when changing the input data. I made it clear that only after the damaging event is it possible to present the data in such way that it will match the theory.

4.3 Procedure to Be Followed After Issuing a Seismic Warning (January 1995)

From the seven warnings issued from the end of October to the end of December 1994, four were followed by events of local magnitude above 2.5. In two cases the underground working places were found to be too dangerous to continue with mining and, as a result, were abandoned. With one warning still in place, it became clear that a procedure for handling this type of information had to be formulated. Issuing a seismic warning had at least two practical consequences. It indicated that a larger-size event (or events) could be expected, but, on the other hand, it also motivated monitoring of the situation. There might be ways of reversing the situation and enough time for taking some precautionary actions. As the introduction and use of the seismic warning concept in the 5B area was becoming practical from the seismic point of view and the record showed that the method had credibility, follow-up procedure had to be implemented. These procedures had to contain two separate elements. The first was a way of passing down information and the second involved the actions that had to be taken by those responsible for safety and mining. By January 1995, when a seismic warning was issued, the seismologist would discuss it with the rock mechanics officer working in the area. The rock mechanics officer would then report this to his section head. After a discussion in which the seismologist was involved, the rock mechanics officer contacted the section manager and gave him a copy of the seismic data, in the form of a time plot. No formal report at this stage was prepared. It was understood that the section manager would then make decisions regarding safety. The rock mechanics department recommended that the following actions take place after a warning:

(a) Ensure that the support in the area of concern is up to standard.
(b) Install additional temporary support at the face and ASG (advance strike gully) gullies.
(c) Ensure that the escape routes are clear.
(d) Decrease backfill to the face by these measures:
    (i) 4.4 m to stay as is
    (ii) 7.0 m reduced to 4.4 m and keep two rows of props.
(e) Sweeping to be kept as near to the face as possible.
(f) Add additional escape routes in the middle of the panel through the blasting barricade.

In addition, the following should be implemented:

(g) Minimize the number of workers in the area at one time.
(h) No visitors should be allowed into this area.

By the beginning of 1995, it was expected that the seismic station cover throughout Vaal Reefs would be increased to the extent that the concept would be implemented as a matter of routine in many other working areas and the problem of response would become a very urgent matter. For this reason, some practical guidelines were required as soon as possible. It did not take long because, by the beginning of February 1995, the following procedure was in place.

Procedure to be followed after a seismic warning was issued:

1. After areas of concern have been identified by the seismologist or rock mechanics department, the rock mechanics officer will inform the relevant

assistant mine manager. Should the assistant mine manager not be available, he will inform the mine manager or section manager.

2. The assistant mine manager, section manager, mine overseer, and the rock mechanics officer will then peruse the 1:200 stope sheets and the 1:1000 mine plans and any previous recommendations, in the survey office and satisfy themselves that:
    2.1 The mining sequence is as per rock mechanics recommendations.
    2.2 The panels have 'second escape ways'.
    2.3 Gully leads and siding lags are within standard.
    2.4 The special area declaration must be in place, including access control.
    2.5 The recommended support system complies with the code of practice. (Two rows of RYHP props with headboards, or one row of RYHP props where backfill is to be maintained a maximum of 4.5 m from the face is recommended).
3. All decisions/recommendations taken at the meeting referred to above will be written down by the rock mechanics officer.
4. The mine overseer will visit the panel/panels concerned within the following two days and issue any necessary instructions to ensure compliance with all instructions pertaining to these panels as mentioned above.
5. The strata control officer will audit the panel/panels within two days after the mine overseer's visit and submit a report on his findings to the assistant mine manager and the section manager.

This procedure was still in place by mid-1997.

4.4 Results of the 5B Experiment with the Seismic-Warning Concept (December 1994–May 1996)

Appendix 4.1 lists all 77 cases recorded during the 17 months of the experiment with the seismic-warning concept. Those 17 months started at the end of December 1994 and ended in May 1996. From this list the following can be concluded:

Concept was successful 62 times, which is in 80% of the cases
False warnings were issued five times that is in 7% of the cases
Missed events (no warning issued) happened ten times, i.e., 13% of the cases
Repeated warnings were issued eight times, i.e., 10% of the cases.

The test area covered by the experiment was 1.5 × 0.5 km in size (750,000 m^2). An average polygon for which a warning was given covered an area of 60,000 m^2, which represented 8% of the whole test area. Those 77 cases listed in Appendix 4.1 can be limited to 27 different areas, of which:

18 consisted of one polygon	54 cases	(70.1%)
3 consisted of two polygons	12 cases	(15.6%)
3 consisted of three polygons	4 cases	(5.2%)
2 consisted of four polygons	2 cases	(2.6%)

In five cases (6.5%), the warning was given for the whole test area. The various sizes of areas for which it was possible to issue warnings might indicate that the seismic cover over the experimental area was not sufficient (Glazer 1997). This would be rectified in the near future as during May/June of 1997 the mine installed an additional seven geophone stations in this area.

For the 56A polygon, the seismic warning was given 13 times. Data in Table 4.2 was extracted from Appendix 4.1. During that six month period, the first warning was given in December 1995 and the last in May 1996. The size of this polygon was 60,000 m^2. From Table 4.2, it is evident that the success rate of the concept was very high and that all 13 events took place after the warning was issued. In two cases, the warning was repeated, after which the events took place during the next day or two (Nos. 10 and 11). In one case, a new warning was issued the same day a big event took place (No. 12). On average, an event in this polygon took place every 13 days. The longest time between events was 47 days, and the shortest time span was three days. The average time between the warning and the event was

Table 4.2 Results for polygon 56A

No	Warning	Date issued	Date of event	M_L	Time (days) between		Comments
					Warning and event	Events	
1	X	06/12/95	15/12/95	2.1	9	–	
2	X	20/12/95	23/12/95	2.1	3	7	
3	X	02/02/96	16/01/96	2.3	14	23	
4	X	22/01/96	29/01/96	2.8	7	12	
5	X	01/02/96	07/02/96	2.6	6	8	
6	X	09/02/96	11/02/96	1.9	2	3	
7	X	13/02/96	15/02/96	1.8	2	3	
8	X	20/03/96	03/04/96	2.2	14	47	
9	X	16/04/96	17/04/96	1.9	1	13	
10	X	29/04/96 05/05/96	08/05/96	2.2	9 2	20	Warning repeated
11	X	10/05/96 14/05/96	15/05/96	2.3	5 1	6	Warning repeated
12	X	15/05/96	18/05/96	2.3	3	3	Warning reissued
13	X	21/05/96	30/05/96	2.7	9	11	

6.5 days. Table 4.2 indicates that this time varied from 1 day to 14 days. The ratio of these two average values is as high as 2.0. This indicates that there was definite merit in the concept. If one takes into account the variation in time between consecutive events and that there is no periodicity involved, then it must be clear that all warnings were issued on the basis of seismic information. It is very unlikely that such high success rates could be by coincidence (Glazer 1997). The time between issuing a warning and the event taking place is very important from the safety point of view. In the case of the 56a polygon, 12% (that is, two warnings) were followed by an event in the next 24 h. In eight cases (47%), the event took place during the next three days. The longest time between the warning and the event was two weeks.

4.5 Case Studies

All case studies, where applicable, refer to Appendix 4.1, which is a table listing all cases of the 5B experiment (for example, Ref 1/15 refers to position 15 of the table in Appendix 4.1).

4.5.1 Changes in Pattern of Seismicity as a Result of Changing the Mining Sequence

An interesting interaction between the character of seismic activity and the sequence of mining was observed in one of the working areas. This area was covered by seismic polygon 54 and included working places 70–54 and 70–55. Figure 4.7 illustrates the changes in the character of seismic activity with changes in mining sequence.

From April to July 1995, the development took place with very limited seismic activity. From July to mid-September 1995, mining panels A towards the west (see Fig. 4.8) resulted in an increase of seismic activity. An increase in strain rate (cumulative apparent volume) can be seen, and the stress (energy index) started to indicate that rock had reached an unstable state. Soon thereafter, events of local magnitude below 1.6 took place ($\mathrm{Log}_{10}E < 6.5$). From September 1995 to January 1996, mining of the lag panels B towards the north resulted in a further increase of the seismic activity. Mining this lag increased the rate of cumulative apparent volume (strain). Several events of M_L above 1.6 occurred. From January 1996 to April 1996, panels C were mined toward the north, and the lag did not exist anymore. At the same time, panels D were mined along the Dip Dyke in the eastward direction. This resulted in an overall decrease in seismic activity with large events limited to the Dip Dyke area. There was a noticeable decrease in the slope of the cumulative apparent volume. Once the pattern of seismic activity of the area

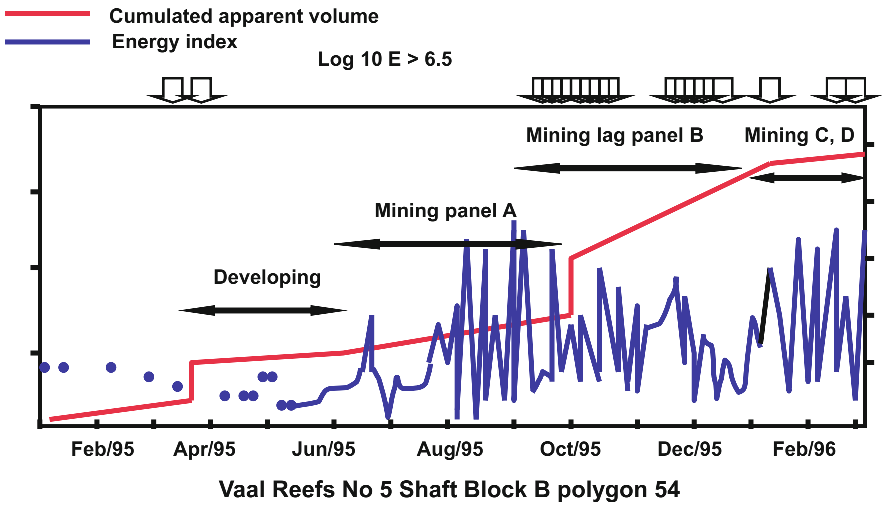


Fig. 4.7 Observed changes in seismic character due to changing the mining sequence

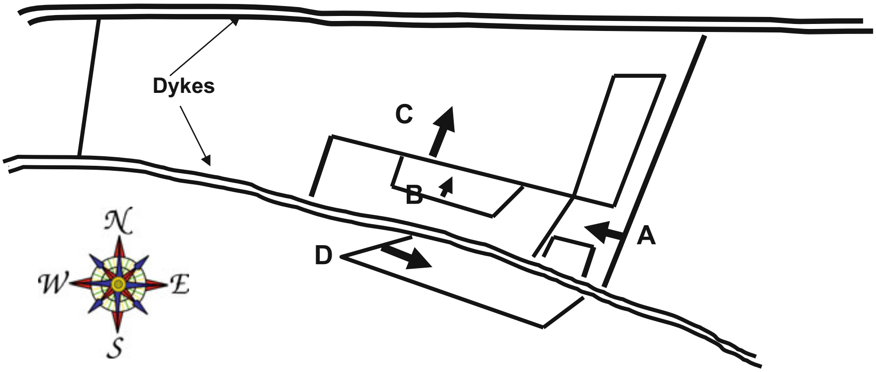


Fig. 4.8 Mining sequence at working places 70–54 and 70–55

was identified, the success rate of forecasting improved. The first strong event of $M_L = 2.7$ took place on the 16 July 1995 and was missed (Ref 1/18). On 30 August 1995, a warning for this area was issued and then repeated on 20 September 1995, and an event of $M_L = 2.1$ (Ref 1/23) took place on the 22 September 1995. Table 4.3 lists events above $M_L = 2.0$ recorded in the 54–55 working areas, from mid-June 1995 to the end of January 1996 with references to Appendix 4.1.

There were in total 18 seismic events. In three cases, the event was missed and one false alarm was given. In 14 cases the warning was successful in the sense that an event took place from a couple of hours up to 14 days later. All those warnings enabled production personnel to increase supervised inspections of mining layouts

Table 4.3 Seismic warnings in working place 54–55 (September 1995–January 1996)

Reference	Polygon	Warning date	Event date	Warning time (days)	M_L	Notes
1/18	54		16/07/95		2.7	Event missed
1/23	54b, 56	30/08/95 20/09/95	22/09/95	23 2	2.1	Warning repeated
1/24	54b, 56	22/09/95	25/09/95	3	2.6	
1/25	54	20/09/95	29/09/95	9	2.3	
1/27	55s	04/10/95	04/10/95	2 h	2.1	
1/28	55–56	12/10/95	12/10/95	6 h	2.7	
1/29	54	16/10/95	16/10/95	2 h	2.2	
1/30	54	20/10/95	27/10/95	7	2.2	
1/31	54		07/11/95		2.5	Event missed
1/32	55s		08/11/95		2.5	Event missed
1/33	55–56	06/11/95	10/11/95	4	2.5	
1/35	54	22/11/95	30/11/95	8	2.1	
1.36	55s		01/12/95		2.5	Event missed
1/39	55w	14/12/95	15/12/95	1	2.8	
1/43	55s, 54	28/12/95	30/12/95	2	2.1	
1/44	54	28/12/95	03/01/96	6	2.5	
1/45	55s	28/12/95	11/01/96	14	2.9	
1/46	55s	12/01/96	12/01/96	10 h	2.6	
1/47	54	08/01/96				False warning

and supports in the sections that were likely to be affected by a seismic event. If follow-up inspections had indicated that the safety of employees was at risk, they would then have been evacuated the specific area. Cement packs and rapid-yielding hydraulic props were used to support the panels, and they bore the brunt of all the large events, minimizing rock-burst damage and injury to workers (Nicolau 1996). The support used in this area proved that conventional support might be superior, or at least equal to, the claimed benefits of extensive backfill (see Sect. 3.3.4).

4.5.2 Change of Mining Sequence in the 5B Area Due to Seismic Information (September 1995)

The geology of the 5B area is very complex. A number of dykes and faults intersect the area. Figure 4.9 illustrates the area geology. The main features are the dykes

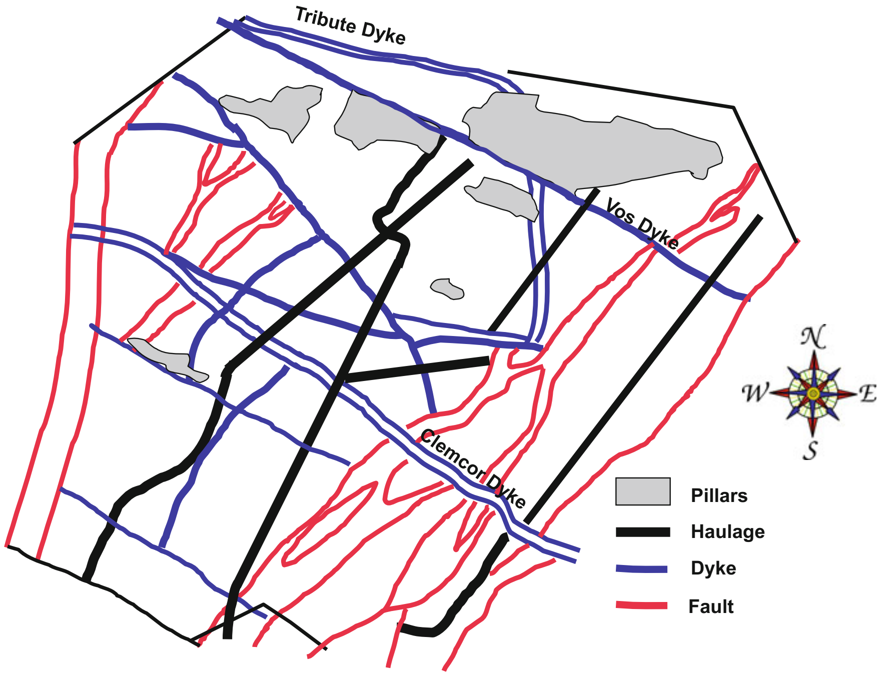


Fig. 4.9 Plan of 5B area mining and geology

(Clemcor, Vos, and Tribute) that run in NW–SE direction, while the main faults (with 50–100 m throw) run in the general direction of NE–SW. Those two types of discontinuities intersect with each other at numerous places.

The mining area itself is limited and very often determined by those geological structures. The 5B area was known for its high level of seismicity which often manifested itself with events above $M_L = 3.0$. To combat seismic hazards, various strategies were in use. Those included extensive use of backfill and of hydraulic props and synchronisation of the blasting times. Also, a number of bracket pillars were designed and left behind. All those strategies were based on the assumption that the main seismic hazard was connected with the Tribute Dyke. Information and data coming from the 5B seismic sub-network changed this perception. It was established by the middle of 1995 that the main source of strong seismic activity in this area is not the Tribute Dyke, but an area south to it, where the Vos Dyke intersects several minor faults. Based on this information, a new mining sequence for this area was introduced. In the area where the Vos Dyke intersected the faults, a bracket pillar of width 25–40 m was left. A number of other reef pillars were left along the major faults and dykes. The general mining strategy was to mine, where possible, away from geological discontinuities. Mining adjacent to geological features was changed to 90° to the structures with a series of up-and-down dip panels. All panels that were out of this new sequence were stopped. The stope support was changed from a stiff unyielding to a yielding type. As a consequence, the amount of production from this area decreased, but, on the other hand, the number of damaging seismic events also decreased. The change in this mining sequence was implemented in mid-September 1995. As a result of the new mining strategy, the mining levels were reduced, but more consistent gold and tonnage production was achieved. The number of accidents decreased, and substantial costs was saved because of the reduction in opening operations due to seismic-related damage (Nicolau 1996).

4.5.3 Seismic Warning Dated 11 May 1995 (Polygon Outside the Experiment Area)

This example describes the follow-up procedure after grounds for issuing a seismic warning was detected in polygon TRIBUTE2. At the time, this polygon included underground working places in mining section 56. It was found that all the panels in this section were mined in proper sequence, all of them had second escape ways in place, and they were clear. It was then decided to implement, with immediate effect, existing recommendations with regard to use of two rows of hydraulic props with headboards in every working place. This recommendation, at that time, wasn't implemented due to a shortage of these props. Action to overcome this problem became a priority. An underground inspection within the next couple of days was to take place to ensure that the recommended support was in place. The warning was cancelled on the 20 May 1995. The warning of 11 May 1995 was based on a limited amount of data. The follow-up actions that were taken improved the underground safety standards and were therefore not a wasted effort from the point of view of the mining personnel.

4.5.4 Seismic Warnings for Areas with Limited Seismic Cover or Based on Uncertain Data

By mid-1995, the seismic section had issued several warnings for places that were located outside the experimental area which had low density seismic station cover. There were also cases of recording, just for our own information, seismic warnings that were based on very limited or not very clear trends. The success rate for those cases was much lower than for the experimental area, but was still high, at a level of about 40%. Unfortunately, we did not keep detailed information for those cases. In many instances, I found it difficult to make a decision, especially when there recently was a seismic-related accident on the mines. On the other hand, giving an official warning could result in saving life, while, on the other hand, issuing a warning, especially for areas with insufficient seismic cover, could jeopardize implementation of the concept that had already been proven to work in the experimental area. This was, at the time, seen as a high risk as further implementation was dependent on the results. This was not a problem to be solved by scientific approach so this was also a moral dilemma. As I was no too sure of how to resolve this dilemma, I presented it at a forum of mine managers in July 1995. In regard to these problems, the following was decided:

1. Seismic warnings are to be made official for areas outside the experimental area
2. In areas where seismic station cover is poor, those areas should be subject to periodic examinations depending on the level of seismic activity
3. Where unclear instability occurs in areas of good seismic station cover, warnings should be issued. In areas where seismic cover is insufficient, the warning should only be made when the unclear situation resolves itself one way or the other.

What follows are minutes of a meeting held on the 27 March 1995, subsequent to a seismic warning given for working areas 64 E5 55 and 66 E5 56 which were located in 5E block. This block, at the time, had low-density seismic station cover and was outside the experimental area. The mining sequences were found to be in order. The second escape routes were in place but had to be made safe as a priority. The support was found to be up to standard. A special-area declaration was made for this area, which meant that a limited number of people could be there at the same time, and no visitors are allowed. During the next three days, the mine overseer was to visit the place for an inspection.

Minutes of a meeting held on 27 March 27 1995, following the alert at 56 E5 55 and 66 E5 55

1.1 The overall mining sequence for the area was scrutinized on the 1:1000 sheets. The sequence is in order.
1.2 Individual working places were scrutinized on 1:200 tope sheets. At 66 E5 55, the following points were highlighted:
    1.2.1 Panel 15 is lagging against the Makrap Dyke.
    1.2.2 Panel 13 was mined ahead of panel 15 in order to complete over stoping of the off-reef excavations.
    1.2.3 Panel 13 is stopped and mining in panel 15 is continuing. Panel 15 will lead against the Makrap Dyke.
    1.2.4 Panel 13 has no siding. This panel was stopped and the ground between ASG and the 4 m throw fault will now be mined.
1.3 Second escape ways are in place. The previously damaged wide raise through the Makrap Dyke should however be drilled, grouted, meshed and laced as soon as possible as was previously recommended.
1.4 Special area declaration is in place. The support at 66 E5 55 raise 2 changed from 1.1 × 1.1 m Apollo packs to 0.9 × 0.9 m Durapacks. A new special area declaration was made for this area.

1.5 The recommended support for this area complies with the code of practice. RYHP's should be used in all panels as recommended.
1.6 The Mine Overseer indicated that he will visit these working places on March 30, 1995. The Rock Mechanics Officer will do a follow-up visit thereafter.

An event of $M_L = 2.6$ took place in this area on 4 April 1995, that is, six days after the warning was given.

On 5 May 1995, a warning was issued for a large area of 8L (No. 8 Shaft Vaal Reefs). This area of about 4 km^2 was, at that time, covered only by the Regional Seismic Network, so the information was based only on relatively large events (above $M_L = 1.0$ to 1.5). In spite of this fact, the warning was successful in the sense that an event of $M_L = 3.2$ occurred in the evening of the same day. Figure 4.10 illustrates a typical precursory curve, where the seismic softening indicates instability for the area. The softening curve (apparent stress index) was below one from October 1994, while the event of $M_L = 3.1$ (Log_{10} E = 9.11) took place only by mid-April 1995, i.e., six months later. This example is only one of a number where in back analysis, based on a small amount of input data, such instability could be seen so clearly. What is interesting in this example is the fact that only two months before the $M_L = 3.1$ event, there was a visible increase in seismic activity (beginning in February 1995). This increase in seismic activity should alert the seismologist to begin some data analysis for the area. Such an increase in seismic activity in some cases could be observed before large events, but on the other hand, there were also examples in which the seismic activity decreased before a large event.

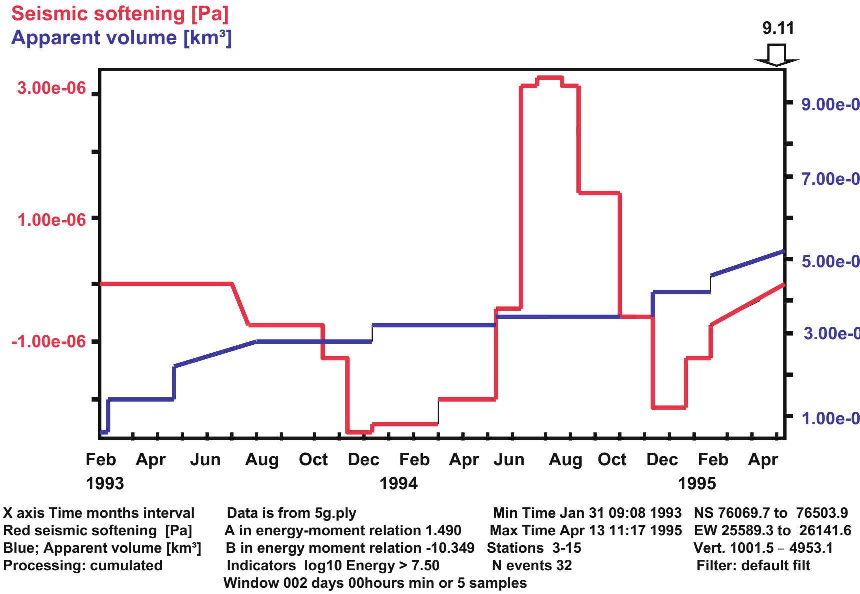


Fig. 4.10 Seismic softening for a big polygon with incomplete data set

4.5.5 Correlation Between Larger Seismicity and Production Stoppages

An interesting problem from a practical point of view is the influence of mining on a rock-mass volume that is already in a highly stressed condition. An answer to this problem in practice would mean control of rock-burst conditions. It would be beneficial to the mine to know if it is possible to avert an event taking place by some planned action. For example, would slowing down the production rate or stopping the mining operations for some time result in reversing the detected seismic-warning conditions? It would be difficult or practically impossible to stop a working place just to test such a concept. Next are three examples where, after issuing the seismic warning, the mining operations were stopped only by coincidence. In two cases, this decrease in mining operations was due to a long holiday period (4–5 days), and, in the third case, blasting was postponed for a couple of days due to sweeping operations taking place. In the latter case, the rock was broken according to call, but not enough gold was coming out of the gold plant. The first example illustrated by Fig. 4.11 might indicate that the instability is reversible, at least at some still-unknown stage. This figure shows two instabilities that can be seen by the drop in stress index.

The first drop in stress index values was from mid-January 1995, and it was followed by a seismic event of $M_L = 2.8$ (Log_{10} E = 8.70) at the beginning of March 1995. The second instability started to manifest itself at the beginning of

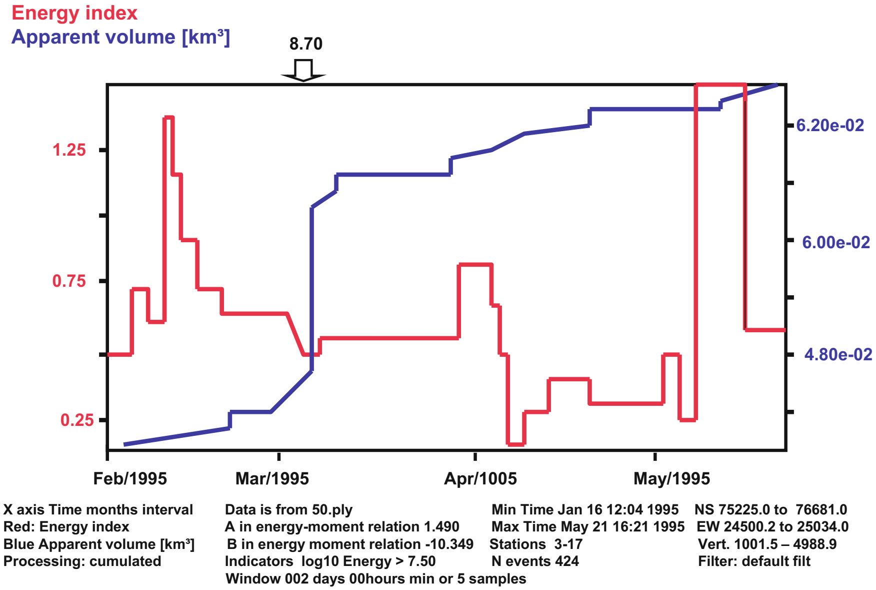


Fig. 4.11 Instability and mining activity—Example 1

April 1995. A warning was given, based on a drop in the stress index and an increase in cumulative apparent volume rate. Just after it was given, the Easter holidays started and lasted practically the entire week, so mining operations stopped totally. There is a clear indication that during this period the seismic activity dropped down, only to pick up again at the beginning of May 1995. In spite of large changes in stress index values, the curve of the cumulative apparent volume stayed flat. The event, which, according to experience with this type of data should have taken place, did not occur.

Figure 4.12 presents the second example recorded during the same time period but in a different part of the mine. Here again, we had similar precursory behaviour of the stress index at the beginning of April, that ended with an event of $M_L = 2.5$ ($\mathrm{Log}_{10}\,E = 7.82$) almost immediately afterwards. After this event, the recorded data indicates that this rock-mass volume was still in an unstable condition, through it had a drop in the stress index. Again, because of the Easter holidays, there was no production in this area, and the event of $M_L = 3.4$ ($\mathrm{Log}_{10}\,E = 9.59$) took place only when the production returned to normal operation. In this case, stopping the mining operations probably resulted in a larger-sized event than that which could take place if the mining operations had been continuous. These two examples are from outside the experimental area of 5B.

The third example is from polygon 54 (Ref 1/49), where a relatively distinct pattern of seismicity could be seen. Every time the stress index values decreased, this was then followed by a seismic event of local magnitude above 2.0 (Fig. 4.13). This area, because of this pattern recognition, became one of the best predictable

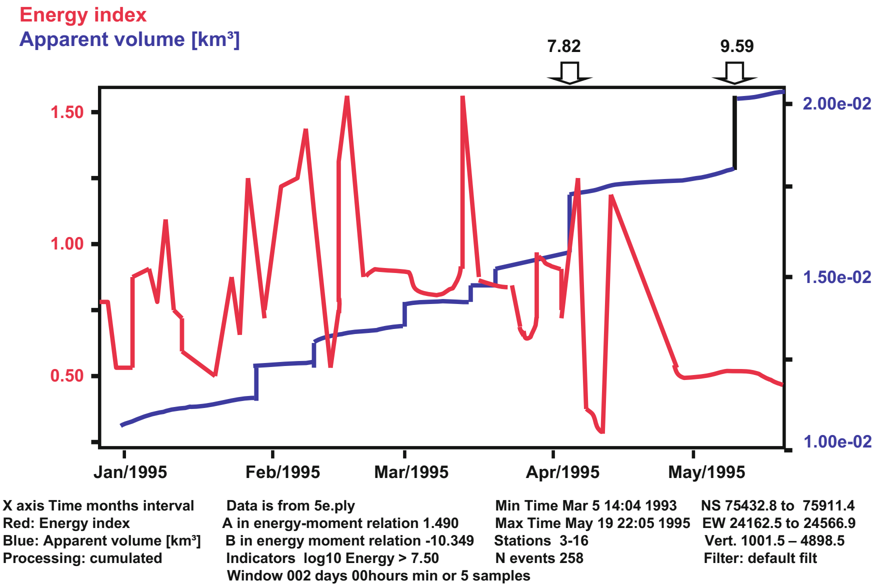


Fig. 4.12 Instability and mining activity—Example 2

polygons. This pattern then changed from November 1995. A warning was given on the 20 October 1995 for the event $M_L = 2.5$ of 27 October 1995 (Ref 1/30). The next event on the 07 November 1995 of $M_L = 2.5$ was missed (Ref 1/31). The instability reported on the 22 November 1995 resulted in a relatively small event of $M_L = 1.8$ on 24 November (Ref 1/34)—for more details in regard to instability and the size of an event, refer to Sect. 4.6. The event of $M_L = 2.1$ of 30 November was preceded by a warning eight days before it took place, that is, on the 22 November 1995 (Ref 1/35). The seismic warning issued on the 2 December 1995 (Ref 1/37) was then followed by an event of $M_L = 1.7$ on 7 December 1995. This latter event is not shown in Fig. 4.13. From this figure, it is evident that there was a significant drop in seismic activity for two time periods, viz., 29 October to 2 November 1995 and for 7–21 November 1995. These two periods of decreased activity resulted from the cessation of blasting and general sweeping operation taking place. The seismic pattern that allowed for easy predictions was changed. A number of events were not predicted. From this example, the following conclusions can be made:

1. Underground activity influences the character of seismicity.
2. Once normal mining operations (blasting) begin, strong events start occurring again.
3. In order to correctly interpret seismic data, the mine seismologist must know not only the local geology of the area, but must be involved in planning of the mining operations.

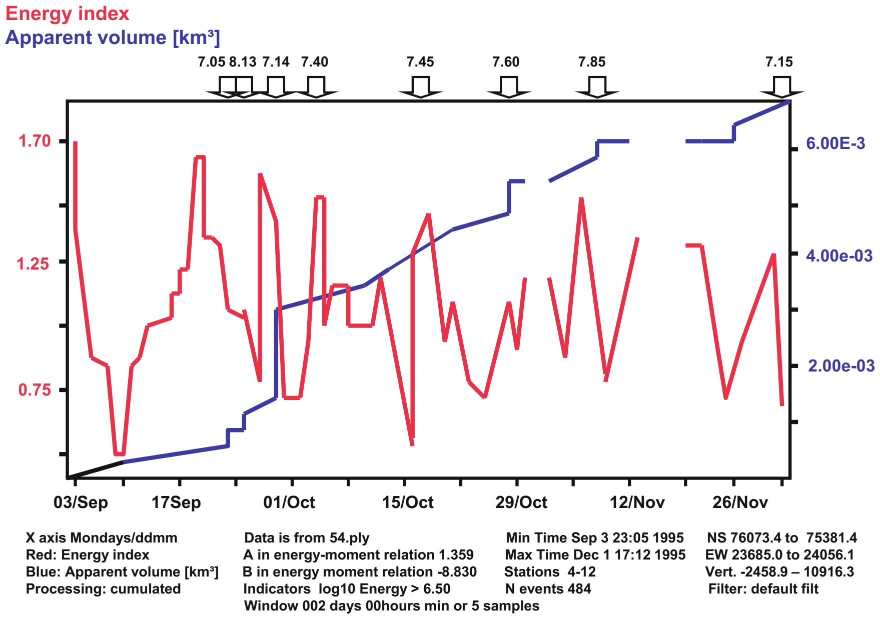


Fig. 4.13 Instability and mining activity—Example 3

A case similar to the previous one was reported for polygon 56a, for which a warning was issued on 22 January 1996 (Ref 1/50). There was no blasting in this area for the next four days. An event of $M_L = 2.8$ occurred two days after the blasting resumed on 29 January 1996. From the above examples, it is difficult to conclude if stopping the mining operations would result in a seismic event not taking place. From a physical point of view, it is obvious that the accumulated energy has to be in some way released. Probably, continuous mining operations would release it in a continuous way, which could be of benefit to the mining operations. There are examples (Sect. 4.5.2) suggesting that the effects of even large energy releases due to seismic events on underground excavations can be controlled by correct mining sequences and support strategy. One could expect that continuous mining would result in an uninterrupted release of energy by average-sized events of M_L between 2.0 and 2.5.

4.6 Instability, Time, Polygon and Size of the Seismic Event—Some Observations

At the start of the 5B experiment, certain assumptions were made in regard to the size of the seismic events that were to be forecasted. At the end of 1994 and the beginning of 1995, we believed that the larger the event, the easier it would be to predict. For this reason, the aim at that time was to predict only the damaging events, that is, events above $M_L = 2.5$. The first event that was predicted (Ref 1/1) was of $M_L = 3.4$, which took place on 30 December 1994. On 13 February 1995, a warning was given for polygon 5se. This area had not experienced an event of magnitude above $M_L = 1.0$ for the previous two years. Twenty- three days later, on 8 March 1995, this area experienced an $M_L = 1.4$ event. A warning for this area was shared by the mining personnel, and, prior to this event, they had improved their support standards. A similar situation occurred when a small event of $M_L = 1.7$ (Ref 1/10) took place in polygon PILLAR14. This warning was given on 24 March 1995, and the event took place on the 25 March 1995, that is, only one day later. The instability indicating this event was in shape and size comparable to any other one. There are other examples indicating that the instability is relative. In other words, it is not possible, on the basis of apparent stress index alone, to predict the size of the future event. Its size can sometimes be estimated only on the basis of experience, when a certain pattern is recognized, but, as experience indicates, this is not always the case. It seems that the cumulative apparent-volume slope is a better indicator of the event size. It is not always a clear indicator, as the stress index is for small events, but it seems to work better for large values of rock mass and larger events. The reason for this might also be the number of events that contribute to its value.

Figure 4.14 shows an example where the slope of cumulative apparent volume very clearly changes from September 1994, and, during the next couple of months,

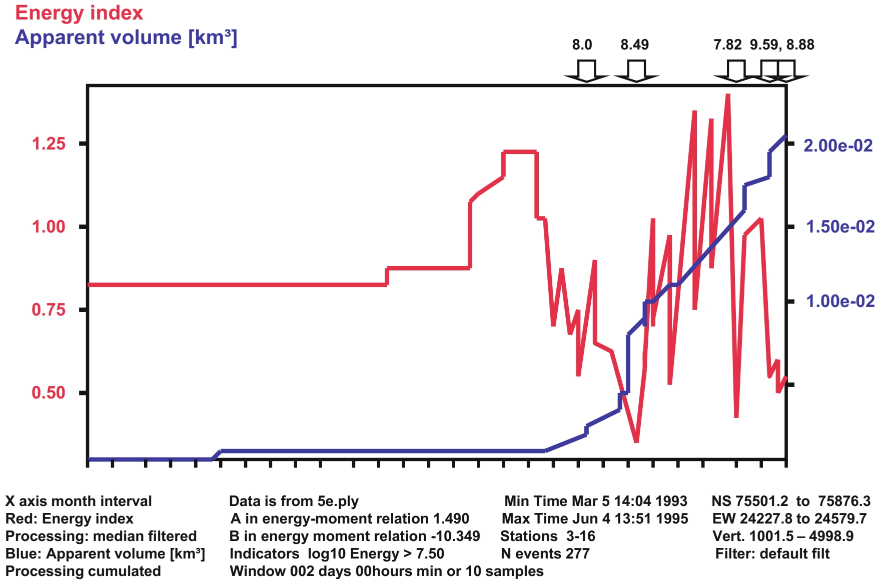


Fig. 4.14 Cumulative apparent volume slope and large damaging events

there were a number of large events ranging from $M_L = 2.5$ to $M_L = 3.4$ (Log_{10} E = 8.0 to Log_{10} E = 9.6). The size of the polygon is about 1 × 1.5 km. The area is located between mined-out grounds, which is on three sides of the polygon. For this reason, the strain rate is very high and is accompanied by large stress drops resulting in the occurrence of large events.

It is interesting to note that, some of those large events were predicted, as for exampler the event of $M_L = 2.6$ of 4 April 1995, for which a warning was given eight days before, that is, on 27 March 1995. The $M_L = 3.4$ event of 7 May 1995 was also predicted. The first warning was issued on 6 April 1995, and the second one ten days before the event took place, that is, on 28 April 1995. Those cases are not listed in Appendix 4.1, as the area in which those events took place is outside the experimental area.

The cases listed in Appendix 4.1 show an interesting trend as far as the success rate for certain sizes of events are concerned. This data indicates that 95% (21 out of 22) of events in the magnitude range $M_L = 2.1$–2.3 was predicted. Above this magnitude, the prediction success rate slowly drops and is 80% (28 out of 35) for magnitude range $M_L = 2.4$–2.9. Then it drops to 57% (4 out of 7) for events with magnitudes above 3.0. This trend might indicate that the network configuration (sensitivity) or the polygon sizes that we were using were right for the magnitude range $M_L = 2.1$–2.3 (see Sect. 4.4) and too small for larger magnitude events. It is probably connected with input-data filtration. There are examples that indicate that the big events can be predicted by the instability that is based on medium-sized events ($M_L = 1.0$–1.5) and recorded over a wide area over a time span of a couple of months. It seems logical that the larger the event, the bigger should be its preparation zone and time. On the other hand, the bigger the size of the polygon, the less valuable is the information for practical purposes. The relationship between the event size and its preparation time and volume should be investigated in more detail.

At the beginning of the 5B experiment, it was believed that better filtering techniques will result in longer warning times. From accumulated experience, the following conclusions in regard to warning times can be made:

1. It is not possible to estimate the warning time only on the basis of seismic information. The factor that might help is the character of the rock-mass response to mining. But experience indicates that this character can change for a number of reasons, such as changes in mining activity or when mining faces approach dykes or faults
2. By June 1995, it was observed that the time span between the warning and the resulting event is equally divided between three spans of time

"Short" time span (up to 1 day)	30% of warnings
"Medium" time span (1 to 7 days)	32% of warnings
"Long" time span (longer than 7 days)	38% of warnings

3. At the same time (June 1995), it was observed that 78% of events that occur after a warning take place between 14:00 and 21:00 that is, directly after the blasting time

The above observations apply to all warnings given up to June 1995.

The importance of the correct size and shape of a polygon to be used to look for instability is shown by an example illustrated by Fig. 4.15. This figure shows that for the time period from mid-January to the end of April 1995, two large events occurred in this polygon, the first one of $M_L = 2.5$ (Log_{10} E = 8.15) on 7 March 1995 and the second one of $M_L = 2.6$ (Log_{10} E = 8.24) on 27 April 1995. The instability for the first event is very clear. There is a significant drop in the energy index starting about seven days before the event occurred. Also, the slope of the cumulative apparent volume indicates a rapid increase in strain rate. After the event occurred, the cumulative apparent slope flattens. After the event of 7 March, the stress index oscillates around the same fixed value practically to the end of the graph. The event of 27 April 1995 was not preceded by such visible changes in cumulative apparent volume rate or stress index. One might say that there is some change in the slope of cumulative apparent volume from about 19 April 1995, but it is not as clear as for the first event. It is also interesting to note that the activity rate for the whole time period is constant, with one exception. It increased just after the first big event, around 11–13 March 1995. This example indicates that the choice of polygon was correct only for the first of the two events. In order to detect the instability that had to occur before the second event, this polygon should have been changed. The slight change in the cumulative apparent volume rate should have been an indication for an experienced seismologist to experiment with the polygon

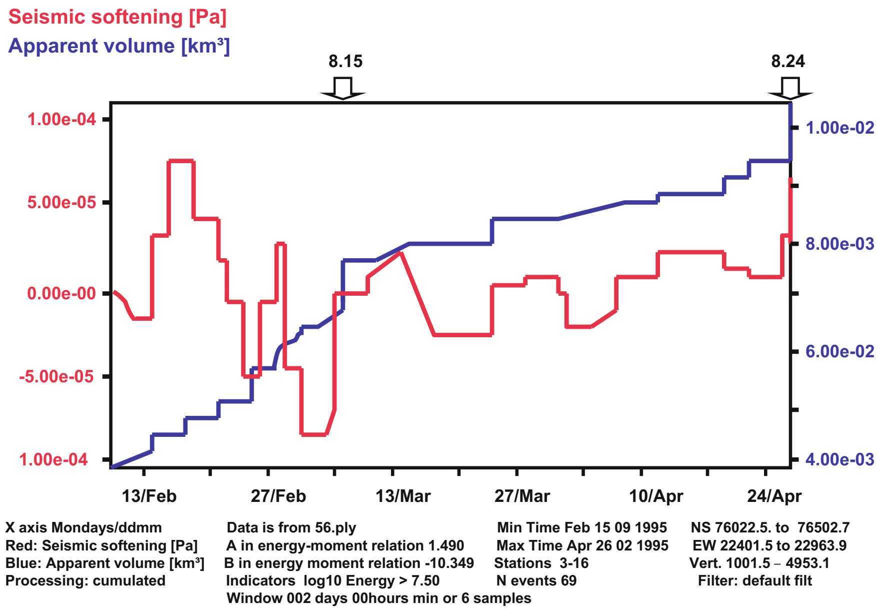


Fig. 4.15 Polygon size shape and instability

location, size, and shape. This type of work was routine for the mine seismologists working at Vaal Reefs.

Finding the right polygon still doesn't mean that it will resolve the problem. There is still a matter of data filtering. Next is an example which indicates that the kind of filter applied to the stress index is important, and, in some cases, different smoothing functions will produce different shapes of the curve. This example was recorded on one of the sub-networks, which were part of the Regional Seismic Network. On 8 March 1997, an event of $M_L = 2.5$ occurred in the area of this sub-network. This event was preceded by a number of events of M_L above 1.0. The size of this polygon is 200 × 200 m.

Figure 4.16 shows the time history that was analysed and was used to issue a warning on 27 February 1997 (arrow). The reason for the posting of this warning was the increase in the slope of cumulative apparent volume. There is also a clear drop in the stress index at the time of the warning. During the next few days, the stress index increased from its minimum value, while the steep gradient of the cumulative apparent volume continued. There is a visible increase in seismic-activity rate. Note that there is a drop in activity rate before the $M_L = 2.4$ event of 5 January 1997. The stress index then drops down again only to increase once more. This is followed by an event of $M_L = 1.1$. After this event, the slope of cumulative apparent volume remains steep, the energy index drops again, and the $M_L = 2.5$ event occurs nine days after issuing the warning. The filtering in the case of data presented in Fig. 4.16 was at zero days or seven samples.

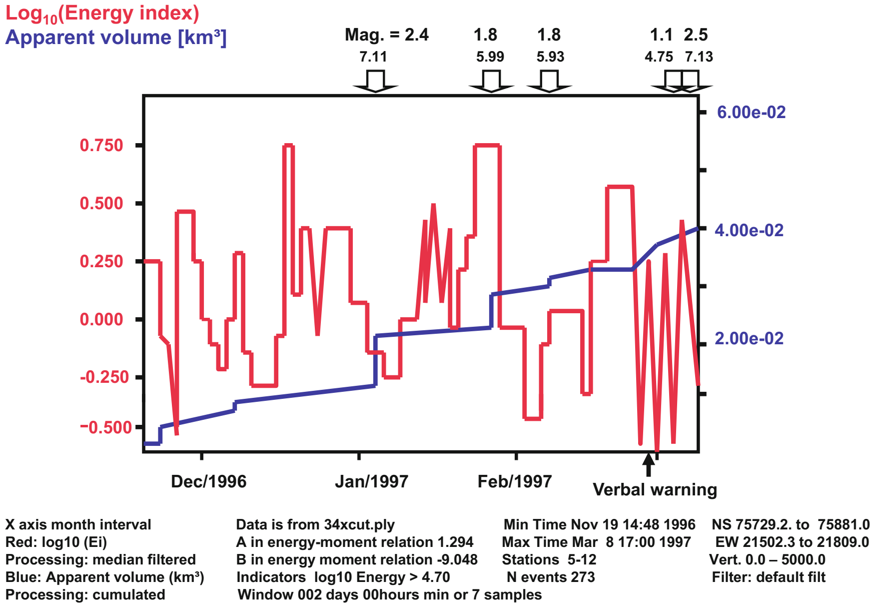


Fig. 4.16 Time history used for data analysis to issue a warning for event of 8 March 1997

Figure 4.17 illustrates the time history of the stress index and apparent volume for the same data, but using a different filter of ten days or 30 samples. This was done in back analysis after the event of 8 March 1997 had already taken place. In

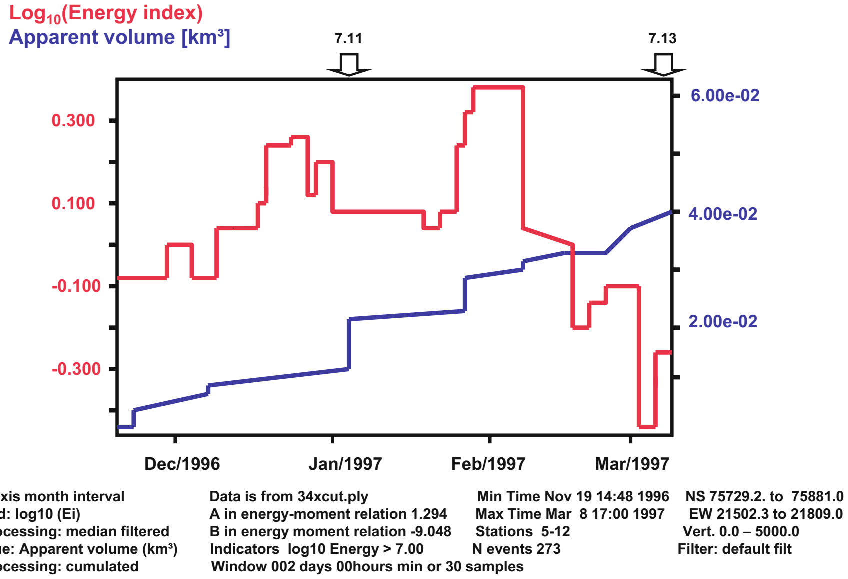


Fig. 4.17 Back analysis of data after the event of 8 March 1997

the case of Fig. 4.17, the precursory behaviour of stress index is clear and visible a month before the event. Note that this filter is not as good as the one used in Fig. 4.16, where the drop in stress index is clearly visible that time for the previous event of $M_L = 2.4$ of 5 January 1997.

These last two examples indicate that data analysis is very difficult and that the time history will depend not only on the selection of the proper input data (polygon), but also on the parameters of the smoothing filters. This fact makes prediction very difficult, and its success depends on how well the area is known to the seismologist.

4.7 Blast-Time and Mining-Strategy Changes for Working Places Located Along the Same Geological Discontinuity

On May 26 1995 (Ref 1/14), a warning was issued for 56b polygon, which was located close to the Vos Dyke. After eleven days, two events occurred, of $M_L = 2.5$ and $M_L = 2.2$ within twelve minutes of each other. Two days later in the same area, two people were killed due to a rock burst from the Vos Dyke, which was much closer to the face than the plans indicated. This rock burst resulted from blasting the panels located along the Vos Dyke in a different shaft (No, 2), away from the location of the accident.

On June 28 1995 (Ref 1/17), a seismic warning was given for polygon 56a, an area also located along the Vos Dyke. As a result, the panel was stopped and drilling indicated that the dyke was much closer to the face than expected. Probably because of this, the mining in that place was then stopped permanently, and the event did not take place. This is an example of an extremely successful warning, in spite of the fact that it was not followed by a seismic event. In this working place, located close to the dyke, a seismic event could have injured or killed people, as the recorded seismicity indicated that the dyke was highly stressed. Based on this type of information, it was decided to scrutinize blasting times for mining areas in the vicinity of the Vos Dyke. At that stage, that time varied from 14:10 in the 2K area of No. 2 Shaft to 16:10 in the 5B area at No. 5 Shaft. In order to minimize risk, it was then recommended that the earliest blast time be 15:20 for all production sections. This recommendation was then put into practice, and, to date (May 1997), there were no fatal accidents associated with the Vos Dyke. It was also decided to minimize the number of working places that are located along the same seismically active fault or dyke. These two actions that resulted in increased underground safety were due to the fact that the area had good seismic cover, and professionals were making correct use of the recorded data.

4.8 Analysis of the Apparent Stress Concept and Its Application by a Rock Engineer on Request of the Production Manager of No. 5 Shaft in January 1996

This analysis was done for the period from the end of December 1994 to 16 January 1996 and included an analysis of events with local magnitude above 2.0, due to anticipated seismic damage. It was found that during this period of time, 46 of these events occurred, of which 35 were preceded by a seismic warning, and, in eleven cases, the events took place without any warning. The success rate based on these figures was 76%. For those 35 events, the time span between the warning and the event's occurrence is presented by data listed in Table 4.4.

Analysis of those 35 events for which the seismic warning was issued and their warning times indicated that

- The warning time decreased during the period December 1994 to December 1995
- The warning success rate increased during the last part of 1995 and at the beginning of 1996

While the first fact is undesirable, as it leaves less time to prepare the underground working places for a seismic event, the second indicates that the area's pattern of seismicity, that is, its response to mining, changed with time. This change in rock-mass response to mining, if recorded by continuous seismic monitoring, could be used to increase the seismic-warning success rate. On the other hand, this information should also be used to increase the level of supervision in regard to the support-standard implementation. As far as the practical aspects are concerned, the implementation of the seismic-warning concept in the area resulted in a change of sequences and a change in the face-support strategy. The changes in sequencing were as follows:

1. General sequence is to mine away from seismically active geological structures.
2. Mining sequences adjacent to geological discontinuities were changed to be orientated 90° to the structure.
3. Bracket pillars were left against known seismically hazardous structures.
4. Out of sequence panels were stopped, and this resulted in a reduction in the number of panels mined.

Table 4.4 Time span between seismic warning and event occurrence

Number of days	Percentages (%)	Portion of total
1	29	10 out of 35
2–3	23	8 out of 35
4–7	17	6 out of 35
8–14	25	9 out of 35
15–28	6	2 out of 35

The change of support strategy from stiff, unyielding stope support in a highly seismically active area to a yielding type of supports resulted in less damage to stope panels (this last observation was made in regard of panels in 68–55 to 68–57 lines).

4.9 Analysis of Seismicity at No. 5 Shaft for the Period February–July 1995

Originally this analysis was done on the request of the assistant manager of production at No. 5 Shaft, and, together with rock engineering reports, was used to change the mining strategy. During this period, the Regional Seismic Network recorded the following number of events at No. 5 Shaft Vaal Reefs as listed in Table 4.5.

The total number of recorded events depends on the performance of the network. In general, when there are some problems with the network, then this is reflected by the number of small events recorded. For example, the number of events of M_L below 0.0 is low in June. This means that some of the stations were not operational, probably because of problems with communication or power cables that could have been destroyed due to damage resulting from large events. From Table 4.5, it is clear that the number of recorded events in the magnitude range M_L 1.0–2.0 has dropped from 35 in February to 20 in May and July. This was considered a very unfavourable situation because those events release a lot of accumulated energy from the rock mass and at the same time are not strong enough to cause risk to life or result in damage. At No. 5 Shaft, the network recorded many small events resulting from blasting. They were located in the vicinity of the stope faces and were the result of rock-mass fracturing after blasting. Larger events are associated with geological features. As far as those are concerned, their number decreased in the time period February–July 1995. This indicated that, because of the actual mining sequences at that time, the energy was accumulating in the faults and dykes. This energy stayed locked when events of magnitude 1.0–2.0 were not taking place. At that time, it was obvious that this energy accumulation at some future time

Table 4.5 Seismicity recorded at No 5 Shaft Vaal Reefs (February 1995–July 1995)

Month	Local magnitude M_L				
	Below 0.0	0.0–1.0	1.0–2.0	Above 2.0	Total
February 1995	526	256	35	9	826
March 1995	426	268	31	13	738
April 1995	384	174	23	8	589
May 1995	365	112	19	6	502
June 1995	258	224	20	6	508
July 1995	714	402	20	4	1140

Table 4.6 The A and B values

Month	A-values	B-values
February 1995	0.448	0.187
March 1995	0.501	0.037
April 1995	0.448	0.182
May 1995	0.464	0.391
June 1995	0.401	1.160
July 1995	0.440	0.978

would result in damaging seismic events taking place before the mining out the area. In fact, we had such events in February 1997. In order to analyse seismicity in the shaft at that time, I calculated the mean apparent stress index for each month. This regression line is described by:

$$\mathrm{Log}_{10}\sigma_a = \mathrm{A}\ \ \mathrm{Log}_{10}\mathrm{M_o} - \mathrm{B} \tag{4.1}$$

The results of this analysis are listed in Table 4.6.

While the A values (slope) for the six months remain almost constant, there is a change in the B values (offset). The B values in general are higher toward the end of the analysed period. This change in the B value indicates that, for an event of the same seismic moment, more energy was released during June and July in comparison to earlier months. Table 4.7 presents the released energy-per-moment magnitude for the time period February–July 1995.

From this, table it appears that, on average, events above $M_L = 2.0$ in July released twice the amount of energy as they did during the period February to June. In practice, this means that in July there were fewer big events (Table 4.5), but every one of them on average had a greater damaging potential compared to those that took place during the months February to June. This supported the conclusion that at the present time mining strategy in No. 5 Shaft resulted in locking the energy in dykes and faults and not allowing them to release the energy in a way that would be safer for mining operations.

Finally, the analysis of values of cumulative energy and moment versus number of events above $M_L = 2.0$ (Table 4.8) confirms that at the time there was a significant change in the seismicity character for the month of July. From Table 4.8, it was clear that there was a drop in the cumulative moment values from February to

Table 4.7 Time-related changes in released seismic energy-per-moment magnitudes

Month	Released seismic energy (J)		
	Mm = 1.0	Mm = 2.0	Mm = 3.0
February 1995	1.2E+05	1.7E+07	2.9E+09
March 1995	2.9E+05	5.4E+07	9.7E+09
April 1995	3.2E+05	1.8E+07	9.7E+09
May 1995	2.7E+05	4.4E+07	6.9E+09
June 1995	3.4E+05	4.5E+07	5.6E+09
July 1995	5.8E+05	8.7E+07	1.3E+10

Table 4.8 Time-related changes in released seismic energy per moment magnitude

Month	Cumulative energy (J)	Cumulative moment (Nm)	No of events above $M_L = 2.0$	Energy per event
February 1995	3.2E+07	2.8E+12	9	3.5E+06
March 1995	3.0E+07	2.3E+12	13	2.3E+06
April 1995	2.1E+07	2.0E+12	8	2.6E+06
May 1995	1.8E+07	1.8E+12	6	3.0E+06
June 1995	1.6E+07	1.7E+12	6	2.7E+06
July 1995	2.9E+07	1.5E+12	4	7.3E+06
Average 1995	2.4E+07	2.0E+12	7.7	3.1E+06

July, and this drop was not reflected in the cumulative energy values. The ratio of cumulative energy per month to the number of large events (above $M_L = 2.0$) for July is twice as large as the mean value for the whole period.

From this analysis, the following was concluded

1. There is a significant change in the pattern of seismicity in July in comparison to the period February to June.
2. Seismic data indicates that during the month of July 1995 the situation at No. 5 Shaft worsened, when compared to the period February–June.
3. Analysis of seismic data indicates that the present method of mining is locking up the faults and dykes, not allowing the release of energy in a continuous manner.
4. Analysis of seismic events indicates that during July large events released more energy than in the period February–June.
5. There is a potential for the occurrence of much larger, and much more damaging, events in the future.
6. Safety and bracket pillars were designed and, in general, mining towards dykes was stopped. Mining now took place along the dykes. In practice, we were not sure how wide these pillars should be because we did not know the exact position of the dykes. This should be established as soon as possible by drilling.

These conclusions were accepted by mine management, and as a result the mining strategy for the whole area was changed (see Sect. 4.5.2). This example illustrates the use and practical application of seismic information in the mining environment.

4.10 Limitations of the Method

The seismic warning concept was formulated in 1993. Practice indicated that, even with some expected advances in seismology, there is no way of establishing the timing of the event itself. It is therefore not possible to estimate if the event will occur within hours or weeks. During the 17 months of the experiment, the following was observed:

27% of events took place within 24 h after issuing the warning.
51% of events took place within three days after issuing the warning.
49% of events took place between four and 23 days after the warning (with one after 41 days).

The stress index proved to be very reliable in providing detailed information, while the cumulative apparent volume had more of a regional application. This is probably due to the fact that events might also take place when the strain rate stays constant, whilst there is a drop in the stress. Where timing of an event is concerned, there are two factors to consider. The first one is related to the time when a change in the energy index is assumed to indicate instability. In early 1994, it was assumed that this could be an important factor in issuing the warning sooner and would therefore benefit the mine. That was not the case. It could have been that the recorded data, as a result of the network configuration, was not good enough to "back time" the instability-discovery time. There was other important factor that came to our attention. Experience showed that the underground conditions undergo constant changes—they do not remain constant. This is revealed by the continuous changes of the energy index, even in a small sized polygon and over a short period of time. This could be true providing that the index itself was calculated in the correct way, that is, the energy and the time span was right for calculating the A and B values of the regression line. Complicating the matter, we were still not sure if a straight line approximation is correct. Another factor that contributed towards these changes in the stress-index values was the accuracy with which the source parameters are calculated. The influence of this factor remains unknown as the accuracy changes from recording to recording. It really depends on the number of stations that recorded the event and on their configuration and distances. In many cases, especially for the smaller events, the source parameters could be far from good estimates. Processing techniques for seismograms are based on Brune's model, which works only for the far field. It is possible that, for cases of dense micro-networks, a significant percentage of the seismograms were recorded in the intermediate or near field, thus contaminating the final source parameters.

Other limitations and uncertain factors of the seismic-warning concept were related to separating the areas of interest: the polygons themselves. They were based on three main factors: seismic clusters, geology, and the location of underground working areas. At that time, it was not clear (as it is at present) how to define a seismic cluster and if it should be limited to space only as seen on the monitor by an analyst. This is a very crude way of doing it, and there is need for improvement. The cluster definition should be improved by including the time clustering (Kijko 1996). The time window used was (and still is) arbitrary and dependent on the amount of recorded data. The polygon only includes the geology close to the underground working places. As a result, the events on this or any other intersecting geological features that might contribute to the instability could be located outside the polygon, and therefore not taken into account. Events close to the working areas due to blasting probably do not have much or any contribution.

In summary the method limitations are due to:

- Network configuration
- Accuracy of source-parameter determination
- Accuracy of derived parameters
- Space and time filtering of events

The experiment indicated that the instability is relative and site-dependent. The former means that the instability can be used to predict events of any magnitude providing that there is a sufficient amount of input data. The size of the event can then be estimated on the basis of the seismic history of the area. Site dependence means that the instability itself depends on the underground mining activities and/or the nature of the geological features. Sometimes, an indication of the future event is increased seismic activity and sometimes the opposite effect is observed, wherein seismic activity decreases.

4.11 Conclusions Resulting from the 5B Experiment

At the start of the 5B experiment, certain assumptions were made in regard to the size of the seismic events that are to be forecasted. At the end of 1994 and the beginning of 1995 we believed that the larger the event, the easier it would be to predict. For this reason, the aim at that time was to try to warn only before the occurrence of a damaging events, that is, events above $M_L = 2.5$.

The main conclusions based on the seismic-warning concept at No. 5 Shaft Vaal Reefs 5B Area are as follows:

1. My original concept of apparent stress index, which was formulated at the end of 1990, proved to be very useful for seismic-data interpretation purposes and has found several practical applications.
2. The concept of apparent stress index found several interpretative applications of which one was it application in the seismic warning concept.
3. The application of the seismic-warning concept at the experimental area of No.5 Shaft Vaal Reefs was a success, not only from a seismological point of view, but what is more important, it resulted in increased safety in underground working places.
4. In view of all known limitations, this success might be difficult to understand. It is possible that the concept itself is so straightforward that it does not depend strongly on the quality of the input data. It is also possible that, by chance, the sub-network configuration was optimal and because of that it acted as a data filter.

5. A seismic warning was limited to indicating an area that might experience a seismic event and was not time-specific, and it could not indicate the size of the future event.
6. Despite the fact that the application of the seismic-warning concept was not a fully reliable management tool for combating rock-burst hazard, its potential for improving underground safety was at that time recognised by the mine management. Proof of this was its implementation over the whole of the Klerksdorp mining area, where the number of seismic stations increased from 32 in 1990 to 97 in June 1997.

The seismic-warning concept contributed towards better understanding of the seismicity induced by mining activities. The bimodal distribution of events has already been described in several publications and works, for example, Kijko et al. (1987), Stankiewicz (1989), Głowacka et al. (1992), and Kijko (1996). This bimodal distribution is very evident when analysing the stress-index values for various mining areas, namely those where the mining has reached an advanced stage and those where only development work has taken place. In development areas for the lower moment ranges, there is more energy released than in the well-mined-out areas. The same phenomena can be observed for events located close to working areas and which are caused by blasting. Those events do not contribute towards seismic warning, at least not when the working face is still at some distance from a geological feature. It must be remembered that, in the case of the Vaal Reefs or the Klerksdorp areas, the damaging events take place mainly on geological features (van der Heever 1982; Potgieter and Roering 1984) and are of a different type than those at the West Rand, where the damaging events often occur in stoping (Ortlep 1984) or are connected with pillar failure (Hagan 1990). As in case of seismicity taking place closer to the working area, there also must be some low seismic-moment events associated with dykes or faults. A method for differentiating between these two should contribute towards improving the understanding of the seismic-warning concept. On the other hand, events with large moment do not seem to follow a pattern, as can be observed for medium-sized events (M_L between 1.0 and 3.0), based on the moment—apparent stress relationship. Some observations made while experimenting with the seismic-warning concept indicated that their behaviour is ruled by other factors than that of smaller-sized events. Heunis (1977) made an observation that faults of large displacements (40+ m) present special rock-burst and rock-fall difficulties because the risk of very large seismic event is considerably amplified by their presence. Little is known about the methods of preventing the occurrence of these very large events. According to Gay et al. (1984), there is a very good correlation between the number of events and the total area mined. From the plots of cumulated energy released by seismic events against centares mined, a very interesting conclusion was made. It is that the occurrence of big events seems to be independent of the mining activity. Johnston (1972), after a comprehensive study of mining-induced seismic events from various parts of the world, divided them into two categories. The first category includes events of low- to medium-sized magnitudes, whose event rate is, in general, a function of mining activity. They are located generally within 100 m of the mining faces along some geological discontinuity. Events of the second category are events of high magnitude, are difficult to correlate with mining, and occur on pre-stressed faults. These events are then, in some undefined way, triggered by mining activity.

On 10 February 1997, a large event of $M_L = 4.3$ took place very close to the experimental area of 5B at No. 5 Shaft Vaal Reefs. At the time, no warning was given, as all monitored polygons did not indicate any behaviour that could be used to issue a seismic warning. This event located on the No. 5 Shaft fault, which has a displacement over 100 metres. The main shock was then followed by a number of aftershocks which were located on the fault itself and on the intersecting dykes. The size of those aftershocks was between $M_L = 2.0$ and $M_L = 2.7$. There were in total 20 of them, and they occurred between 10–15 February. There were no events recorded in close proximity of the source of this event prior to it taking place. The only one was the $M_L = 4.3$ event that took place six years earlier on 1 December 1991 From this, one can conclude that the mining-induced seismic events at Vaal Reefs follows a triple-mode distribution, rather than a bimodal one and that those events can be divided as follows (Ebrahim-Trollope and Glazer 1997):

1. After blast events, which are due to fracturing taking place in front of the faces. These are small events of magnitude up to $M_L = 0.5$.
2. Events connected with local d-size faults and dykes. These events are up to magnitude $M_L = 3.0$ and are connected with actual mining operations.
3. Events above magnitude $M_L = 3.5$ that are associated with the regional structures and are connected with the whole mining history of the area.

Experience indicates that some of the events of M_L 2.0–3.0 could be anticipated by prior warnings. Usually, small events are of no consequence to mining safety. Larger regional events above $M_L = 3.5$ seem to be out of the seismic-warning concept range. To conclude, there is one more observation that seems to be in agreement with the seismic-warning system success associated with the event sizes. In Gibowicz and Kijko (1994), there is a graph indicating the mean return periods of seismic events for the whole Klerksdorp Gold Mining District. They were estimated using data from 1972 to the end of 1991. If one superimposes on this figure data based on seismicity recorded from January 1991 to the end of October 1996 (70 months), then there is an agreement between the two curves up to $M_L = 3.0$, after which those two curves deviate. This difference increases proportionally with the increase of event magnitude. From the above, it could be concluded that probably a different law controls events of magnitude up to 3.0, and a different mechanism is in place for events above $M_L = 3.0$.

The results of the practical application of the seismic-warning concept in the test area were a success. The concept success rate for this area was as high as 80%. In view of all the known limitations, this might be hard to understand. It is possible that the concept is so simple and straight forward that it does not depend strongly on the quality of the input, or else the quality of the input is far better than we suspected. Alternatively, it may be that the events in this specific test area were easy to foresee (Glazer 1997). It is clear that the seismic information whilst valuable was not time specific. Experience indicated that stopping mining production does not result in the event not taking place, but rather in delaying it. For this reason, seismic information was used to support all rock-engineering recommendations. A seismic warning is/was strictly limited to indicating an area that in the future might experience a seismic event. Its strength (magnitude) or times of occurrence were both unknown. In other words, seismic warnings were limited to location predictions and, as such at the time, were still in a developmental stage. Despite the fact that the seismic-warning concept at the time was not a fully reliable management tool, its potential for underground safety improvement was recognized by management. This has resulted in the implementation of this concept over the entire Vaal Reefs mining area. It was a costly decision regarding capital expenditure and running costs. A very important aspect of applied mine seismology is its direct impact on safety improvement. The impact of the introduction of the instability concept in the 5B area of the No. 5 Shaft is difficult to quantify, as there are relatively few accidents related directly to specific seismic events. Accidents often occur due to the damage caused by a seismic event or work done related to the repair of seismic damage. For this reason, the general trend of accident statistics for the whole shaft might be used as an indication of the success rate of the instability concept. Figure 4.18 illustrates the trend of reportable accidents from September 1994 to the end of 1995. The procedure for seismic warning was introduced at the end of 1994. There is a general trend that indicates that the accident numbers for the whole shaft dropped by more than half during 1995 (Nicolau 1996). On the basis of such observations, it was decided to apply the instability concept in the other parts of Vaal Reefs. Chapter 5 describes in greater technical detail the Klerksdorp Regional Seismic Network, its sub-networks, and the Vaal Reefs seismic networks which came on line during 1995–1997.

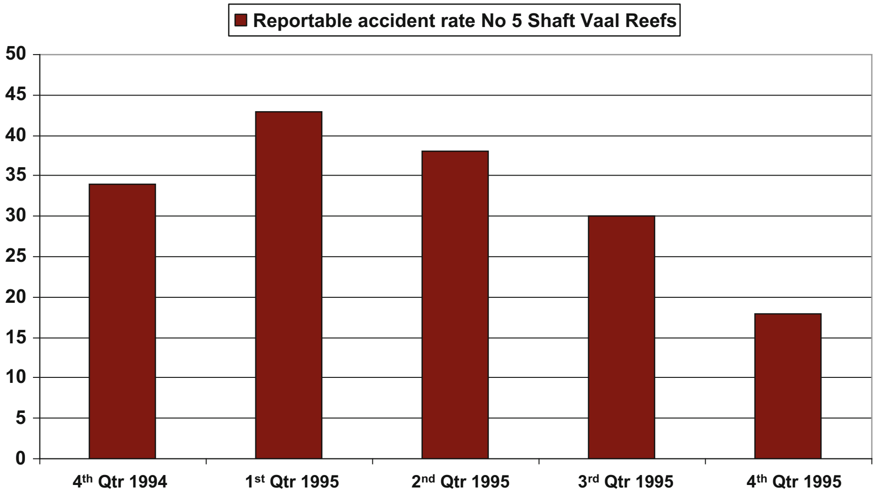


Fig. 4.18 Quarterly reportable accident rate at No. 5 Shaft Vaal Reefs

4.12 Summary and Conclusions

It is obvious that, practically from the start of the experiment, seismic warning as such become secondary to what was really happening. Good seismic cover enabled for accurate predictions of the locations of seismicity, which resulted in the identification of the seismic-hazard sources. It was then, for example, recognised that the location of the problem dyke was actually unknown. For this reason, mining was stopped and drilling after the dyke started. Once the correct location of the dyke became known, this was used in practice and new safer mining sequences were introduced. This new mining layout resulted in less rock being mined, but the mining conditions become safer. The examples presented in this chapter prove that recorded seismicity can be used to improve safety. There were even cases when the underground conditions were defined as too dangerous to continue with mining. As a result, such mining places were abandoned. We did not issue seismic warnings, and then expect the miners to be evacuated from the underground working places. But, something like this happened twice. It turned out that, in one case, the working place did not have a second escape route and, in the second case, the second escape route was not clean and not ready for use. According to mining rules, in these two cases, there should be no mining taking place. After the seismic warning, the mining operations in the area were immediately stopped until the escape routes were in place. In this chapter, there are also examples in which, after the seismic warning, the mine improved the support standard, and there no damaging seismic event took place. As already mentioned, Vaal Reefs management very quickly adopted the philosophy that the success rate should rather be measured in preventive actions taken, rather than in the success of the prediction itself. Several preventive actions were put into practice that included additional safety pillars, changes in mining sequences and directions, and also a review of the mining strategy for the whole 5B area. An interesting case was the one connected with the Vos Dyke were a blast in one shaft resulted in a rock burst taking place in other shaft. As a result, the blasting times at these shafts were coordinated, and the working places along the dyke were reduced. It is important to note that the seismic warnings were used to increase the level of supervision in regard to the support-standard implementation. It is obvious that the seismic warning test resulted in increasing the underground safety. Mine management had practical proof that mine seismicity and mine seismologists are there for the benefit of the mine. Despite the fact that the application of the seismic warning concept was not a fully reliable management tool for combating rock-burst hazard, its potential for improving underground safety was at that time recognised by the mine management. Proof of this was its implementation over the whole of the Klerksdorp mining area. There is no doubt that the seismic-warning concept contributed towards better understanding of the seismicity induced by mining activities.

Appendix 4.1 Data Relating to the 5B Seismic-Warning Experiment

No	Polygon	Warning	Date issued	Date of event	Time span (days)	M_L
1	Pillar 1a	X	28/12/94	30/12/94	2	3.4
2	Pillar 34			05/01/95		2.7
3	5 Bn	X	14/01/95			
4	Trb 2			18/01/95		2.9
5	Pillar 11	X	01/02/95	02/02/95	1	2.8
6	Pillar 34	X	02/03/95	02/03/95	>1	3.3
7	56a	X	03/03/95	06/03/95	3	2.7
8	55–54	X	27/02/95	22/03/95	23	2.7
9	Trb 2	X	09/03/95	25/03/95	16	2.7
10	Pillar 14	X	24/03/95	25/03/95	1	1.7
11	Pillar 34	X	05/04/95 08/04/95	10/04/95	5 2	2.7
12	56	X	09/03/95 06/04/95	20/04/95	41 14	2.4
13	Trb 2	X	10/05/95			
14	56b	X	26/05/95	06/06/95	11	2.5 2.2
15	56a			08/06/95		2.7
16	58	X	29/05/95	09/06/95	11	2.2
17	55, 56, 34, 56a	X	28/06/95			
18	54			16/07/95		2.7
19	34			03/08/95		3.3
20	34			03/08/95		3.5
21	54b, 55, 56a	X	07/08/95			
22	58	X	07/08/95	11/08/95	4	2.6
23	54b, 56 Pillar 14	X	30/08/95 20/09/95	22/09/95	23 2	2.1
24	54b, 56 Pillar 14	X	22/09/95	25/09/95	3	2.6
25	54	X	20/09/95	29/09/95	9	2.3
26	56a	X	20/09/95	29/09/95	9	2.6
27	55s	X	04/10/95	04/10/95	2 h	2.1
28	55–56	X	12/10/95	12/10/95	6 h	2.7
29	54	X	16/10/95	16/10/95	2 h	2.2
30	54	X	20/10/95	27/10/95	7	2.2
31	54			07/11/95		2.5
32	55s			08/11/95		2.5
33	55–56	X	06/11/95	10/11/95	4	2.3
34	54	X	22/11/95	24/11/95	2	1.8

(continued)

(continued)

No	Polygon	Warning	Date issued	Date of event	Time span (days)	M_L
35	54	X	22/11/95	30/11/95	8	2.1
36	55s			01/12/95		2.5
37	54	X	02/12/95	07/12/95	5	1.7
38	54, 55w, 55e, 55s	X	14/12/95	14/12/95	3 h	1.7
39	55w	X	14/12/95	15/12/95	1	2.8
40	56a	X	06/12/95	15/12/95	9	2.1
41	5b	X	18/12/95 20/12/95	1/12/95	3 1	2.8
42	56a	X	20/12/95	23/12/95	3	2.7
43	55s, 54	X	28/12/95	30/12/95	2	2.1
44	54	X	28/12/95	03/01/96	6	2.5
45	55s	X	28/12/95	11/01/96	14	2.9
46	55s	X	12/01/96	12/01/96	10 h	2.6
47	54	X	08/01/96			
48	55–56			13/01/96		2.2
50	56a	X	22/01/96	29/01/96	7	2.8
51	55–56	X	22/01/96	02/02/96	10	1.8
52	56a	X	01/02/96	07/02/96	6	2.6
53	55–56	X	22/01/96	11/02/96	19	2.8
54	56a	X	09/02/96	11/02/96	2	1.9
55	56a	X	13/02/96	15/02/96	2	1.8
56	54	X	12/02/96	15/02/96	3	2.3
57	5b	X	13/02/96 22/02/96	22/02/96 23/02/96	9 1	2.0 2.7
58	55–56, 54	X	23/02/96	24/02/96	1	3.4
59	55w	X	23/02/96	24/02/96	1	2.0 2.6
60	55e	X	23/02/96	25/02/96	2	3.0
61	5b	X	09/03/96	09/03/96	4 h	2.5
62	5b	X	20/03/96	25/03/96	5	2.3
63	56a	X	20/03/96	03/04/96	14	2.2
64	54	X	29/03/96	04/04/96	6	2.8
65	56a	X	16/04/96	17/04/96	1	1.9
66	55–56	X	04/04/96 16/04/96	17/04/96	13 1	1.8
67	55–56	X	16/04/96	24/04/96	8	2.2
68	54 South	X	29/04/96	01/05/96	2	3.0
69	55–56	X	29/04/96	02/05/96	3	2.7
70	56a	X	29/04/96 05/05/96	08/05/96	9 3	2.2

(continued)

(continued)

No	Polygon	Warning	Date issued	Date of event	Time span (days)	M_L
71	54n	X	10/05/96	10/05/96	2 h	2.5
72	56a	X	10/05/96 14/05/96	15/05/96	5 1	2.3
73	56a	X	15/05/96	18/05/96	3	2.3
74	55–56	X	21/05/96	27/05/96	6	2.2
75	55–56	X	27/05/96	28/05/96	1	2.3
76	56a	X	21/05/96	30/05/96	9	2.7
77	5b	X	21/05/96	30/05/96	9	2.6

Appendix 4.2 List of VR Internal Reports (1988–1997)

This appendix lists internal reports dated from 1988 up to 1997. Most of them were written by me. I have the habit of writing reports for myself and an executive summary for the management. In this way, when coming back to the case described in the report, there is a record of all data and a description of what, and why, some action was taken. It made it easy to use this data in my PhD thesis.

Glazer SN (1988) The Vaal Reefs Regional Seismological Network-Configuration Study. Internal Report RS-6-88 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1988) Seismological Needs for Vaal Reefs. Internal Report MISC-90-88 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1989) Klerksdorp Regional Seismic Network. Internal Report RS-5-89 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1990) The Concept of Apparent Stress Internal Report RS-145-90 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1991) Peak Ground Velocity for Mine Tremors Internal Report RS-4-91 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1991) Use of Apparent Stress Concept for Plotting Areas of Different Damage Potential Resulting from Seismic Events Internal Report RS-10-91 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1991) Interpretation of Seismic Data Recorded in the Vicinity of the Clemcor Dyke from 01.09.90 to 31.03.91. Internal Report RS-19-91 Mining

Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1991) Level of Seismic Activity Internal Report RS-55-91 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1991) The No 5 Shaft Seismic Event (X960) on 1 December 1991 Internal Report RS-55-91 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1992) Input of Seismic Data into Rock Mechanics Recommendations. Internal Report RS-5-92 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1992) Use of Scaling Values Internal Report RS-14-92 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN Relation between the Magnitude Values as Reported by KMMA Regional Seismic Network and the Geological Survey of South Africa Internal Report RS-44-92 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1992) Event No 408V of 19 June at No 9 Shaft Vaal Reefs. Internal Report RS-47-92 Klerksdorp Mine Managers Association Regional Seismic Network, Klerksdorp, South Africa

Glazer SN (1992) Concept and Interpretation of Stress Index and its Practical Application in Deep Mining Environment Internal Report RS-51-92 Klerksdorp Mine Managers Association Regional Seismic Network, Klerksdorp, South Africa

Glazer SN (1992) Probability of a Seismic Related Accident at Vaal Reefs Internal Report RS-63-92 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1993) Comparison of Seismicity between Filled and Conventionally Mined Areas (2K and Hartebeestfontain) Internal Report RS-22-93 Klerksdorp Mine Managers Association Regional Seismic Network, Klerksdorp, South Africa

Glazer SN (1993) Seismic Strategy Internal Report RS-46-93 Klerksdorp Mine Managers Association Regional Seismic Network, Klerksdorp, South Africa

Glazer SN (1993) Seismological Report by Dr DdJ Carneiro Internal Report RS-62-93 Klerksdorp Mine Managers Association Regional Seismic Network, Klerksdorp, South Africa

Glazer SN (1994) 5 Year Seismic Monitoring Strategy for Vaal Reefs Internal Report RS-9-94 Klerksdorp Mine Managers Association Regional Seismic Network, Klerksdorp, South Africa

Glazer SN (1994) Introduction of Alert/Alarm Concept at 5B Area. The First Alarm. Internal Report RS-84-94 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1995) Alert/Alarm Concept at 5B Area No 5 Shaft Vaal Reefs Internal Report RS-01-95 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1995) Potential Instabilities Manifesting Themselves Only Hours before the Event Occur. Do We Need to Consider 24 Hour Seismic Cover Allowing Issuing Alarm? Internal Report RS-115-95 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1995) Report Summarizing Instability Concept Implementation for Second Quarter of 1995. Internal Report RS-147-95 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1995) Analysis of Seismicity of No 5 Shaft for the Period February–July 1995. Internal Report RS-147-95 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1996) Qualification of Seismic Hazard for Panel Risk Rating. Internal Report RS-158-96 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Glazer SN (1997) Seismic Event M = 4.5 10 February 1997 at 18H08. Internal Report RS-32-97 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Nel L (1995) Success Rate of the Probability Model for Predicting Seismic Events-Summary. Internal Report RS-186-95 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Nel L (1995) Results of Probability Model. Internal Report RS-218-95 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Retief SJP (1996) Peak Ground Velocity in the Klerksdorp Mining Area. Internal Report RS-146-96 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Stankiewicz T (1997) Analysis of Rejected Events in May 1997 for the Seismic Networks. Internal Report RS-117-97 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Taljard J (1992) Extraction of the Scott Shaft Pillar. Internal Report, Stilfontein Gold Mine, South Africa

Van Oort J (1996) Success of Seismic Monitoring on No 5 Shaft Internal Report ES-06-96 Rock Mechanics Department-North Mine, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

Van Wyk JJ (1991) Rockfall and Rockburst Support Design Internal Report M-24-91 Mining Engineering Division, Vaal Reefs Exploration and Mining Co Ltd, Vaal Reefs, South Africa

References

Ebrahim-Trollope R, Glazer SN (1997) An assessment of seismic monitoring in a deep level scattered gold mining environment. In: SAGA Conference 97, Swakopmunt, Namibia, 28–30 Sept 1997

Gay NC, Spencer D, van Wyk JJ, van der Heever (1984) The control of geological and mining parameters on seismicity in the Klerksdorp 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 107–120

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

Glazer SN (1997) Applied mine seismology. A Vaal Reef perspective. In: Gibowicz SJ, Lasocki S (eds) Proceedings of 4th international symposium on rockbursts and seismicity in mines. Balkema, Rotterdam, pp 227–231

Głowacka E, Stankiewicz T, Holub K (1992) Seismic hazard estimate based on the extracted deposit volume and bimodal character of seismic activity. In: Knoll P (ed) Induced seismicity. Balkema, Rotterdam, pp 45–53

Hagan TO (1990) Pillar foundation failure studies at deep South African gold mine. In: Fairhurst C (ed) Rockbursts and seismicity in mines. Balkema, Rotterdam, pp 65–69

Heunis R (1977) A report on the interim conclusions of the Rock Burst Project 1973–1977

Johnston JC (1972) Rockburst from a global perspective. In: Knoll P (ed) Induced seismicity. Balkema, Rotterdam, pp 63–78

Kijko A (1996) Statistical methods in mining seismology. South African Geophysical Association, Pretoria

Kijko A, Drzęźla B, Stankiewicz T (1987) Bimodal character of the distribution of extreme seismic events in Polish mines. Acta Geophys Pol 35:157–166

Mendecki AJ (ed) (1997) Seismic monitoring in mines. Chapman and Hall, London

Nicolau NF (1996) Interaction between the seismic alert/alarm concept and mining practice at Vaal Reefs. In: Papers and discussions 1996–1997, Association of Mine Managers of South Africa

Ortlep WD (1984) Rockbursts in South African gold mines: a phenomenological view. In: Gay NC, Wainwright C (eds) Rockbursts and seismicity in mines. Symposium of South African Institute of Mining and Metal, Ser. No. 6, Johannesburg, pp 45–50

Potgieter GJ, Roering C (1984) The influence of geology on the mechanisms of mining-associated seismicity in Klerksdorp gold-field. 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 45–50

Prinsloo MJ, Rosenblatt M, Gilroy JAC, Cunningham CVB (1995) Mining a narrow tabular reef at depth with reference to rock breaking and associated support systems. In: Explo 95 Conference, Sydney, Australia

Stankiewicz T (1989) Stochastic model of seismic activity and its application to seismic hazard estimates in mines. PhD thesis, Institute of Geophysics, Polish Academy of Sciences, Warszawa (in Polish)

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

Chapter 5
Status of the Networks in the Klerksdorp Area, June 1997

Implementation of the long-term plan for 1996–1998, as decided in 1994, was based on results of actions taken in 1994–1995. The major factors were the results of implementing the seismic-warning concept in the test area. For the period December 1994 to end of May 1996, the network recorded 77 large, potentially damaging events, of which in 62 cases there was a warning issued. This gave a success rate of 80%. There were two factors that should be noted. The first was connected with the prediction-success rate itself. During this period, the success rate increased from month to month, indicating that the instability concept was implemented in the correct way. The next was that Vaal Reefs adopted a philosophy that the success rate should rather be measured in preventive actions taken than in the success of the warning itself. Several preventive actions were put into practice that included additional safety pillars, changes in mining sequences and directions, and a review of the mining strategy for the whole area.

The experimental sub-network of eight stations at the 5B area of No. 5 Shaft Vaal Reefs was fully operational from September 1994. In June 1997, its extension by six additional stations has been nearly completed. The No. 5 Shaft Vaal Reefs pillar network began operations in October 1995. The No. 2 Shaft Vaal Reefs Seismic Network was operational with some of its stations located in the north part of the shaft from July 1996 and had been fully operational from January 1997. In October 1996, the first seismic warning was given for the north part of No. 2 Shaft, and, for the south part, the seismic-warning procedure was implemented starting in June 1997. The No. 8 Shaft Vaal Reefs Seismic Network had been operational from February 1996 with stations that were located in its south part. At that time, extensions to the north part, as well as to No. 11 Shaft Vaal Reefs, were in progress. The No. 4 Shaft Pillar Network was by that time in an early stage of installation. There were some underground preparation works in progress and the required equipment and cables were on order. For me, there transpired a memorable episode with the regional manager. The technician responsible for the No. 4 Shaft installations told me that he would not be at work for the whole of the next week, because he would be playing rugby for the mine. My answer was that he must forget about

S.N. Glazer, *Mine Seismology: Seismic Warning Concept*,
https://doi.org/10.1007/978-3-319-62353-5_5

rugby as the installations were behind schedule. I was sure that this would be the end of the story. A couple of hours later, but still during working hours, I got a phone call from the regional manager who told me that I must allow the technician to represent the mine in the rugby tournament. As he was playing and wearing the mine colours, he was the injured, in plaster for the next six weeks, and out of action on the shaft. The seismological experience of Vaal Reefs was passed on to Hartebeestfontein G.M. From May 1997, they employed their first seismologist. A sub-network covering the extraction of their No. 4 Shaft pillar was in operation from May 1996. The second sub- network (part of the regional network), also for shaft pillar extraction, was located at No. 2 Shaft and by June 1997 was already partially operational. By the end of 1995, Vaal Reefs had established a concept for seismic monitoring. This was a concept of one central site serving all Klerksdorp shafts and mines, with all sub-networks and networks connected together. Subsequently, the central site was rebuilt and equipped with new computer technology. With this, a decision to increase the number of seismic staff was made. Beginning in June 1994, the seismic central site was manned 24 h a day, on a three-shift basis. This resulted not only in an improved quality of recorded seismic data, but more importantly, all events of damaging potential were immediately reported to the shafts. This enabled them, when required, to send proto teams with no delay, or start opening-up operations directly at the affected areas.

5.1 Performance of the Networks

This section describes the Klerksdorp-area networks as they were in June 1997. At that time, there were four operational networks, and one in an early stage of installation.

Those four operational networks were:

- Klerksdorp Regional Seismic Network
- No. 5 Shaft Vaal Reefs Pillar Network
- No. 2 Shaft Vaal Reefs Network
- No. 8 Shaft Vaal Reefs Network

The network undergoing installation (and planned to be online by the end of 1997)

- No. 4 Shaft Vaal Reefs Pillar Network

Figure 5.1 shows the seismic networks of the Klerksdorp area. Underground stations of the Regional Network are in blue, while the surface stations are in red. Only the Regional Seismic Network had surface stations, three at Hartebeestfontein and four at Vaal Reefs.

The Regional Seismic Network served all three mines of the area, providing general seismic cover. From a typical regional network, as it was in 1990 (see

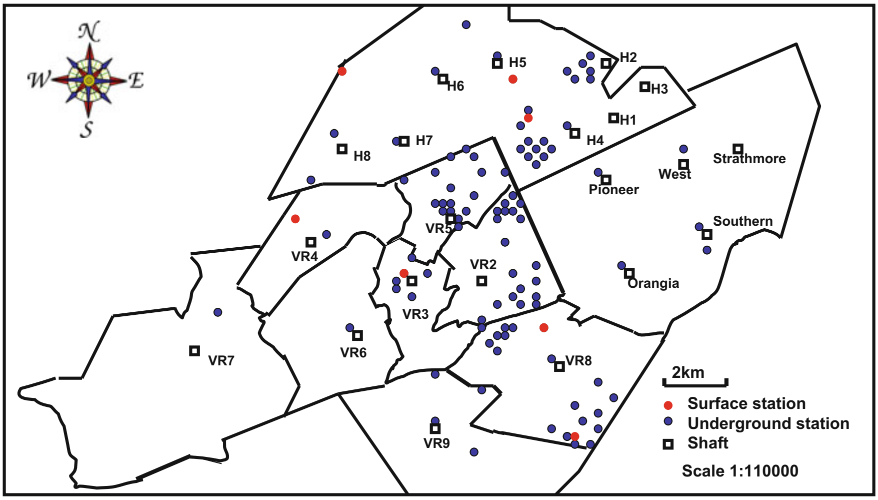


Fig. 5.1 Seismic networks in Klerksdorp area

Figs. 2.3 and 2.12), it evolved into a hybrid network. This was initially due to testing the warning concept at the 5B area of No. 5 Shaft Vaal Reefs where eight stations were added. After the concept proved to be of practical importance to the mine, other sub-networks joined in, this time to introduce the concept to other areas in the most economical way, that is, by making use of the already existing central-site facilities. When it became technically impossible to add new sub- networks to the regional network, several independent networks were put into place. Section 5.3 describes the central site that was used to manage all the networks.

The sub-networks were:

- 5B area of No. 5 Shaft
- No. 1 Shaft Vaal Reefs
- No. 2 Shaft Hartebeestfontein
- No. 4 Shaft Hartebeestfontein

At that time, the 5B sub network was extended to the 5D and 5E areas with the installation of more underground stations. Table 5.1 shows the number of stations of the Regional Network located at each mine.

Table 5.1 Number of regional stations

Mine	Area (km^2)	Number of stations		Total
		Operational	In installation	
Vaal Reefs	107	34	3	37
Hartebeestfontain	57	19	6	25
Buffelsfontain	61	5	–	5
Total	225	58	9	67

Table 5.2 Number of stations of regional network grouped in sub-networks

Sub network	Area (km^2)	Number of stations		Total
		Operational	In installation	
Vaal Reefs				
No. 5 Shaft area B&D	4.7	11	3	14
No. 1 Shaft pillar	0.5	6	–	6
Hartebeestfontein				
No. 2 Shaft pillar	0.2	2	6	8
No. 4 Shaft pillar	0.2	6	–	6
Total		25	9	34

Table 5.2 lists the areas covered by sub-networks and the number of stations.

From Tables 5.1 and 5.2, it is clear that half of the stations of the Regional Network were grouped into sub-networks. Those sub-networks covered areas of intense mining (pillars or remnants). Table 5.3 lists the total number of stations for all the networks in the entire Klerksdorp area. In June 1997, there were, in total, 97 stations operational while another 33 were in various stages of installation.

Presented next are statistics of all the recorded triggers from June 1996 to the end of May 1997. All recorded triggers had to be processed, the noise (false and test triggers) was rejected, and the accepted events were stored in the database. These statistics were done in order to monitor the performance of the network and discover the problems that had to be rectified. From Table 5.4, it is evident that the seismic processors at the Seismic Central Site manually processed between 20,000 and 30,000 events monthly. More than 50% of the seismic data was then accepted and used in the daily analyses. The total numbers of accepted and rejected events for the time period from June 1996 to May 1997 are given in Table 5.4 and Figs. 5.2 and 5.3. Table 5.5 gives the total seismic events processed (December 1996 to May 1997) and the percentage of accepted and rejected events for each network. Table 5.6, and Figs. 5.4, 5.5 and 5.6 provide more detail in respect of the network's performance.

In May, 24,924 events were processed of which 10,075 (40%) were rejected. The highest percentage of rejected events was on kma (70%). On vr5p, vr2, and vr8, the percentage of rejected events was much lower (22, 19, and 37%),

Table 5.3 Klerksdorp area seismic networks

Network	Code	Area (km^2)	Number of stations		Total
			Operational	In installation	
Regional	kma	225	58	9	67
No. 5 Shaft Vaal Reefs	vr5p	0.5	8	–	8
No. 8 Shaft Vaal Reefs	vr8	22.5	10	18	28
No. 2 Shaft Vaal Reefs	vr2	13.2	21	–	21
No. 4 Shaft Vaal Reefs	Vr4p	0.8	–	6	6
Total			97	33	130

Table 5.4 Total number of seismic events recorded from June 1996 to May 1997

Month	Seismic events processed		
	Accepted events	Rejected events	Total
June 1996	6490	12,298	18,788
July 1996	9376	13,974	23,354
August 1996	12,275	15,229	27,504
September 1996	10,616	14,192	24,808
October 1996	12,127	17,478	29,603
November 1996	15,263	15,693	30,956
December 1996	13,060	13,169	26,229
January 1997	16,658	11,773	28,431
February 1997	15,262	9721	24,983
March 1997	11,786	7600	19,386
April 1997	14,299	13,659	27,958
May 1997	14,849	10,075	24,924

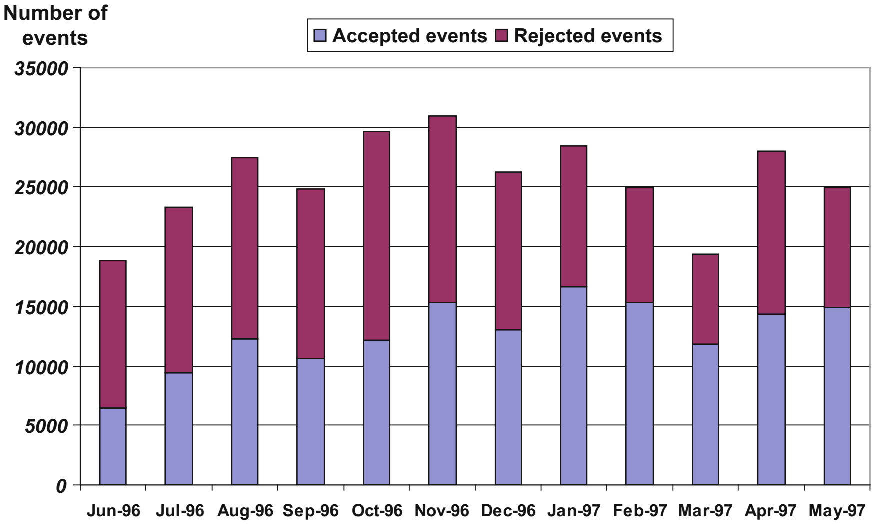


Fig. 5.2 Total numbers of recorded events from June 1996 to May 1997

Events recorded by only one or two stations were rejected by default. With an increasing number of stations, the percentage of rejected events generally decreases. For the kma network, the threshold for collecting events was set to nine stations for the whole area, but for groups it was set to three stations. The number of groups was

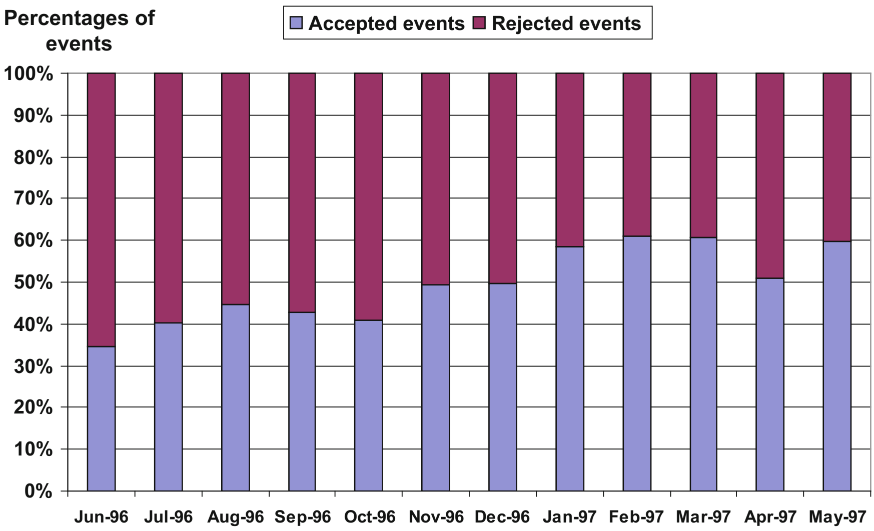


Fig. 5.3 Percentages of accepted and rejected events from June 1996 to May 1997

increased to 18 in order to cover the whole area. The high percentage of rejected "four-station" events was mainly due to wrong associations. There was a large number of rejected events recorded by one station only (35% of all rejected). This was due to the setting of several stations for testing purposes. It seems that there were no losses due to communication problems. For the vr5p network, the threshold for collecting events was set to three stations. The total number of rejected events was 22%, practically the same as in previous months. The vr8 network used the threshold for the number of stations triggering an event equal to four. The new version of the ISS software (7.1) was introduced to this network on 22 May. In order to test the handling of groups by this version, four groups with a minimum threshold of three stations were selected. As a result, there were relatively high (in comparison with previous months) percentages of rejected events with three stations. The percentage of all rejected events was 37%—on the same level as during the previous six months. The vr2 network used the threshold for number of stations equal to ten for the whole area but, for four selected groups, it was set to four stations. The percentage of rejected events was very small—only 18%, but the number of all recorded events was also very small.

5.2 Network Management

By mid-1997, there were 15 members of staff employed by the seismic section. They were divided into three groups, each performing specific tasks that interlinked with each other in order to produce high-quality output information. In order to inform

Table 5.5 Total number of processed events December 1996 to May 1997

Month	Network	Accepted		Rejected		Total
December	kma	2209	25.3%	6525	74.4%	8734
	vr5p	3006	72.4%	1144	27.6%	4150
	vr8	6296	64.9%	3397	35.1%	9693
	vr2	1549	42.4%	2103	57.6%	3652
	Total	13,060	49.8%	13,169	50.2%	26,229
January	kma	2382	35.0%	4417	65.0%	6799
	vr5p	4550	78.7%	1234	21.3%	5784
	vr8	7337	64.2%	4084	35.8%	11,421
	vr2	2389	54.0%	2038	46.0%	4427
	Total	16,658	58.6%	11,773	41.4%	28,431
February	kma	2174	35.0%	4043	65.0%	6217
	vr5p	4468	81.4%	1022	18.6%	5490
	vr8	6612	64.0%	3718	36.0%	10,330
	vr2	2008	68.2%	938	31.8%	2946
	Total	15,262	61.1%	9721	38.9%	24,983
March	kma	2110	38.8%	3323	61.2%	5433
	vr5p	3031	79.3%	790	20.7%	3821
	vr8	5170	64.5%	2842	35.5%	8012
	vr2	1475	69.6%	645	30.4%	2120
	Total	11,786	60.8%	7600	39.2%	19,389
April	kma	2370	23.7%	7610	76.3%	9980
	vr5p	2393	78.6%	653	21.4%	3046
	vr8	8458	62.1%	5165	37.9%	13,623
	vr2	1078	82.4%	231	17.6%	1309
	Total	14,299	51.1%	13,659	48.9%	27,958
May	kma	1865	29.6%	4434	70.4%	6299
	vr5p	4432	78.1%	1243	21.9%	5675
	vr8	6837	63.1%	4001	36.9%	10,838
	vr2	1715	81.2%	397	18.8%	2112
	Total	14,849	59.6%	10,075	40.4%	24,924

each staff member of problems and progress, every day started with a short informal meeting. Additionally, all reports were circulated for everyone’s information.

The three groups were:

- Technical section
- Computing section
- Seismological section

Table 5.6 Number of stations in events that were accepted or rejected in May 1997

No of stations	kma		vr5p		vr8		vr2	
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
1	1	1729	0	13	0	35	0	0
2	0	30	0	4	0	17	0	2
3	241	707	384	638	237	525	0	4
4	424	1280	549	238	3199	2037	807	283
5	401	376	603	110	1607	774	343	66
6	300	113	853	71	1076	333	446	28
7	160	49	1012	74	530	170	10	1
8	95	48	1031	04	107	43	1	0
9	42	23	0	0	81	67	0	0
10	51	27	0	0	0	0	0	1
11	93	30	0	0	0	0	104	10
12+	57	22	0	0	0	0	4	2

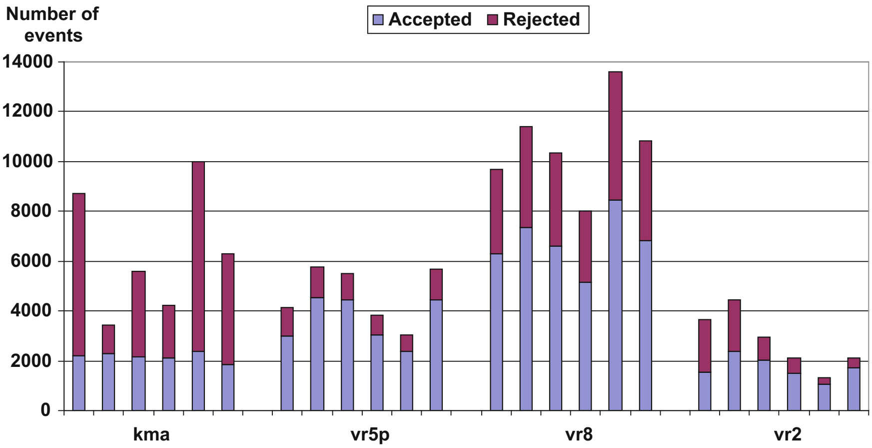


Fig. 5.4 Number of recorded events on each network December 1996 to May 1997

Technical section

This subsection consisted of three technicians, with qualifications and experience in the field of electronics. There was also one trainee technician, who at that time was acquiring formal qualifications in electronics.

Those technicians were responsible for:

- Maintenance of underground and surface-seismic installations and the communication systems (radios, modems)
- New installations and re-installations
- Quality of recorded data

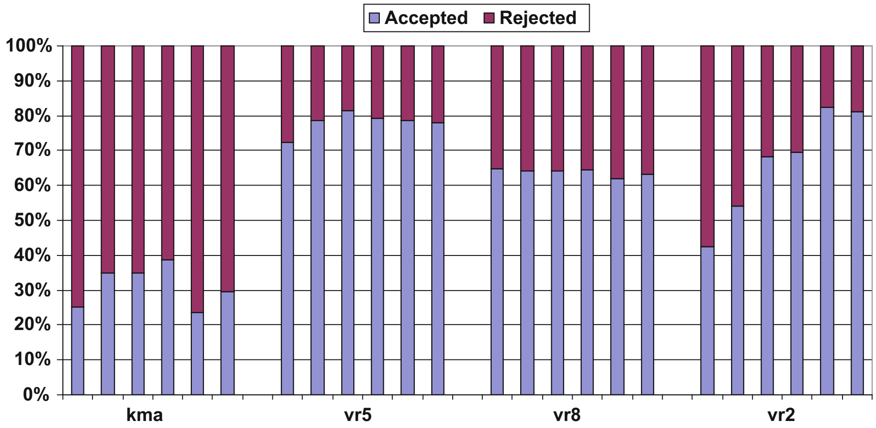


Fig. 5.5 Percentages of accepted and rejected events

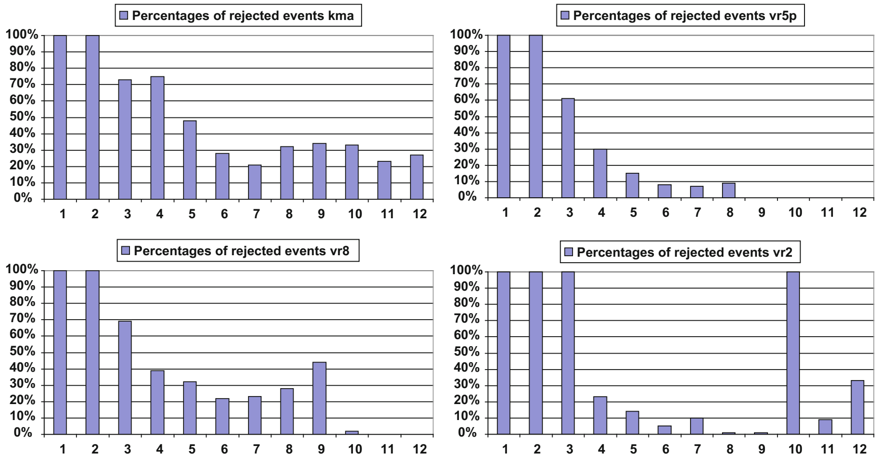


Fig. 5.6 Distribution of rejected events depending on number of accepted stations in May 1997

- Repairs of faulty equipment
- Liaison with shafts
- R&D projects—for example, fast communications modems
- Technical stand-by for major problems (after hours)

Computer section

This sub-section consisted of two computer specialists and four seismic processors. The network administrator and assistant were responsible for:

- Administration and maintenance of software and hardware used by the seismic systems and networks (ten graphic workstations, ten PC's, four Run Time

Systems, network multiplexer, switch, rooter, server, and all peripherals and modems)
- Maintenance of seismic databases
- Programming as required
- Supervision of processors
- Installation and debugging of software
- After-hours stand-by to assist with major problems (through a laptop and telephone modem)
- R&D projects—for example, collecting data associated with seismic related damage

The processors were responsible for:

- Seismic data processing
- Reporting seismic events to shafts and rock mechanics staff on stand-by
- Monitoring the performance of the networks
- Calling up technicians or computer backup to solve problems with the network operation when required

Seismological section

The seismological sub-section consisted of four qualified seismologists (with a degree and experience) and one trainee seismologist. The seismology group was responsible for:

- Seismic data interpretation
- Integration of seismic data into rock engineering recommendations
- Quality control of processed data
- Quality control of network performance
- Routine reports and as required
- R&D projects

The R&D projects in progress at that time were:

- Development of a seismic data interpretation methods and introducing them into rock engineering recommendations
- Relationship between mining sequences and seismicity
- Quantification of seismic hazard using the logistic distribution
- Space-time clustering of mining-induced seismicity
- Strong ground motions for the Klerksdorp area
- Training manual (seismology for mining personnel)

The seismologists had specific networks for which they were responsible. One of the seismologists was responsible for the Vaal Reefs North Operations (Shaft Nos. 1, 2, 3, 4, 5), while the other was responsible for the Vaal Reefs South Operation (Shaft Nos. 8, 9, 11). The trainee seismologist was responsible for the Klerksdorp Regional Seismic Network data, while the Hartebeestfontein seismologist was responsible for the seismic data recorded at his mine. He was not a member of the Vaal Reefs Seismic Section, but he had done a lot of work in the central site, which controls the Hartebeestfontein stations and sub-networks of the Regional Seismic Network. The senior seismologist was responsible for quality control of all networks, and this included the recording as well as the processing parameters. His responsibilities included training of seismologists and running the main R&D projects.

The manager of the network was responsible for:

- Managing and running all networks, which included administration, financial, and technical aspects.
- Planning further development of the networks.
- Supervision and coordination of development work done by the section.
- Liaison with research centres.
- Managing capital projects.
- Training rock engineering staff in seismology.

5.3 Technical Description of the Network's Central Site

All seismic networks of the Klerksdorp area were managed from one central site. Figure 5.7 shows the schematic diagram of the central site, which was centred on the switch. The Run Time System (RTS) of the Regional Seismic Network was

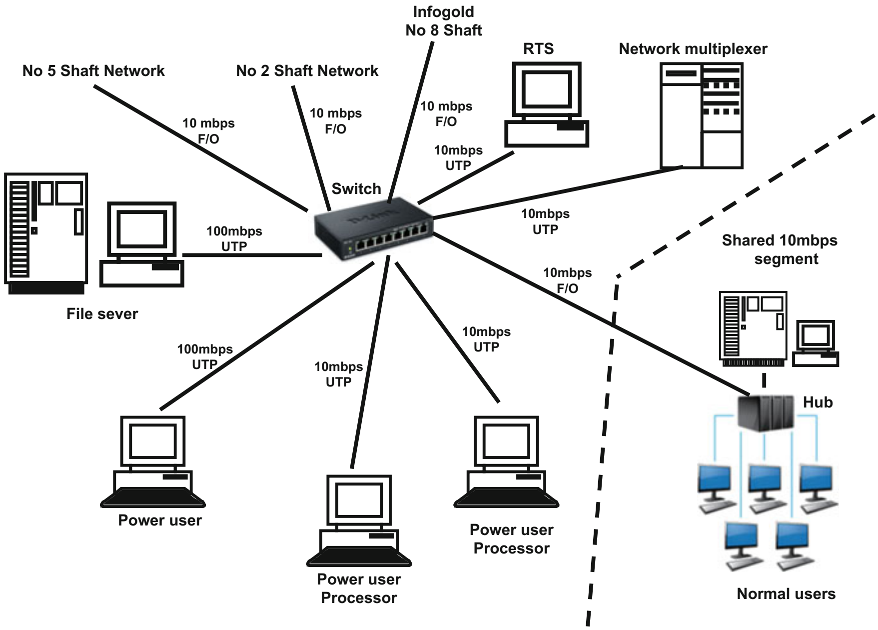


Fig. 5.7 Lay-out of KMMA Regional Seismic Network central site

connected through the switch to the network multiplexer. The power users were the seismic processors and the seismologists, each using a graphic workstation (different types of INDY), that were directly connected to the switch. The file server (16-Gb database) was also directly connected to the switch, which was shared with the rock engineering department through a link between the switch and the hub.

Connected to the switch were the independent networks that had their RTS located at the shafts:

No. 5 Shaft Pillar Network	(vr5p)
No. 2 Shaft Network	(vr2)
No. 8 Shaft Network	(vr8)

The latter was connected through a fibre-optic link (F/O), which was shared with other users and belonged to a mine-wide fibro-optic link. For normal users as the rock mechanics staff, their PC desktops were connected to the hub. A more detailed layout of the Regional Seismic Network central site is given in Fig. 5.8. Here, the centre was the 64 channel network multiplexer, which was connected with the RTS through the switch. The communication from the central site to the stations was from the RTS, and the communication coming in from the stations to the RTS was through the Network Multiplexer. The RTS sent out messages through the following transmitters:

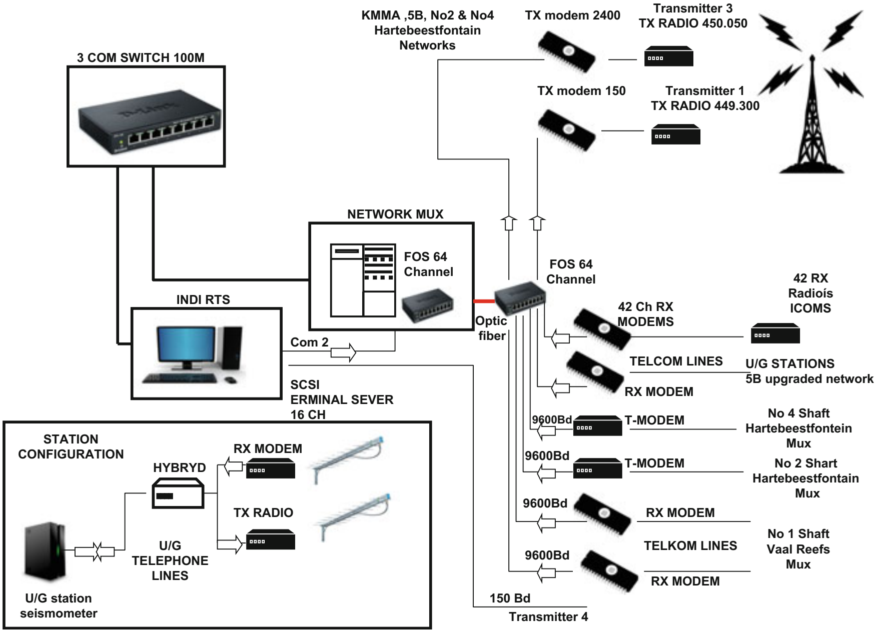


Fig. 5.8 Communication system of the Regional Seismic central site

(a) Transmitter 1, to those stations that had 150-baud communication speed.
(b) Transmitter 2 was used as spare link.
(c) Transmitter 3, to those stations that had 2400-baud communication speed. This was the communication baud rate to which finally all stations would be upgraded, and this upgrade was already taking place. This transmitter was also used to communicate with the following sub- networks

  - No. 4 Shaft Hartebeestfontein
  - No. 2 Shaft Hartebeestfontein
  - No. 5 Shaft Vaal Reefs (5B area sub network)

(d) Transmitter 4150-baud telephone lines to No. 1 Shaft Vaal Reefs sub-network.

Listed below are the separate incoming communications links all at a baud rate of 9600:

- Radio-linked stations
- Cable-linked stations
- Radio linked sub-networks: No. 2 Shaft and No. 4 Shaft Hartebeestfontein) sub-networks and No. 5 Shaft VR 5B sub network
- Cable-linked sub networks of No. 1 Shaft Vaal Reefs

Further technical details relating to the Regional Network and its sub-networks, as well as of the independent networks, are given in Appendix 5.1.

Appendix 5.1 Technical Description of the Klerksdorp Networks (Status End of 1997)

KMMA Regional Seismic Network

The Regional Network (Fig. 5.9) consisted of a RTS (Run Time System), a Silicon Graphics computer, a Network Multiplexer, and a PC-based system with multiple serial ports. Outgoing data was transmitted directly from the communication ports on the RTS system, and all incoming data was received via the Network Multiplexer. Communication between the RTS and the Network Multiplexer took place by means of an Ethernet network (10BaseT). The outgoing data was transmitted by transmitter 1 at 150 b/s, and incoming data was received at 1200 b/s (baud).

The network multiplexer consisted of a PC-based system with a 64 RS-232 ports. These ports were fully software controlled and could be reconfigured by the RTS while receiving and transmitting on a different baud rate (150–19,200 b/s). The network multiplexer was connected to a second FOS unit via two fibre-optic cables in full duplex mode. This fibre- optic connection insured full electrical isolation between the RTS, network multiplexer, and the radios. From the second FOS unit, a RS-232 line connected it to the transmitting modem. This modem converted the RS-232 data to frequency-shift keying (FSK) format and passed it to

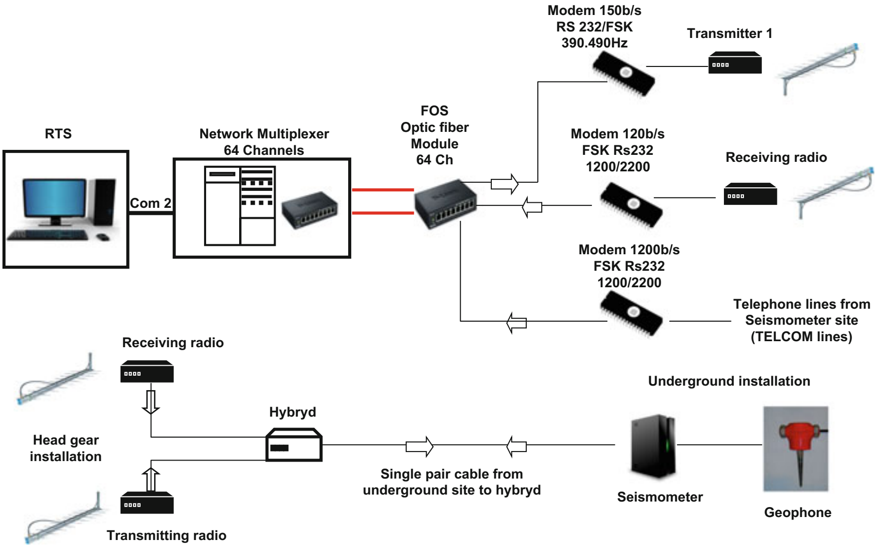


Fig. 5.9 KMMA Regional Seismic Network

the UHF Radio transmitter 1 (449,300 MHz). The frequencies used by the logic 0 or 1 were respectively 390 and 490 Hz.

At the shaft headgear, a radio receiver passed the FSK data on to the hybrid. The hybrid was connected to the underground site with a single pair of telephone wires. The function of the hybrid was to superimpose the receiving data (from the RTS) and the transmitting data from the IS, PS, or MS on one telephone line. At the underground site, the seismometer could be an Intelligent Seismometer (IS), Processing Seismometer (PS), or a Multi-Seismometer (MS). The data was transmitted at 1200 b/s in a FSK format, and the two carrier frequencies were 1200 hand 2400 Hz, respectively. The data from the underground site to the RTS followed the same line to the hybrid, then to a separate radio transmitter. At the central site, a radio receiver or a direct telephone line passed the data to a modem, which converted the FSK to RS-232 format. The incoming data was channelled to the FOS unit on receiving ports (RS-232). This means that 55 serial ports were communicating with the RTS at any one time. A time update was sent to all seismometers every five minutes via transmitter 1.

The No. 5 Shaft 5B Seismic Sub-network (As It Was Until June 1997)

The 5B sub-network (Fig. 5.10) was originally part of the regional network, but, due to the low data rate of 150 b/s, the transmitted data from all the stations became too much and we were forced to split the two networks. Both were still transmitting

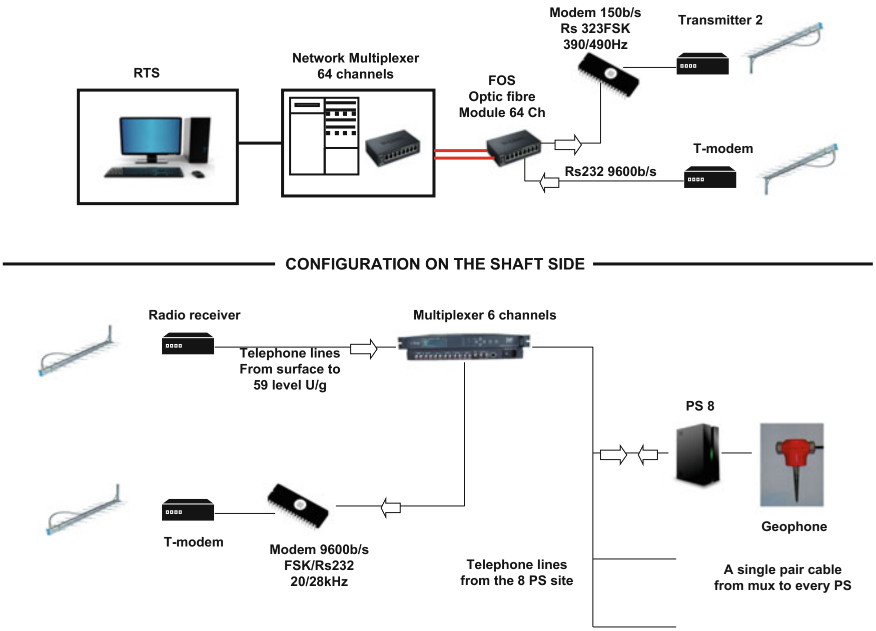


Fig. 5.10 No. 5 Shaft 5B area seismic sub-network

at 150 b/s. All the communications that were relevant to all the stations in the No. 5 Shaft area were channelled to a separate port and transmitted trough the FOS units to a modem (converting the RS-232/FSK) and then to the radio transmitter (transmitter 2). On the shaft side, a radio receiver passed the incoming data to a multiplexer, which sent the data to all eight processing seismometers. The processing seismometer sent the outgoing data 1200 b/s in FSK (1200 and 2200 Hz) format to the multiplexer. The function of a multiplexer was to compress the outgoing data from a number of stations in a network into a single communication link. The data was transmitted in FSK format at 9600 b/s to a modem on the surface. This modem converted the FSK data to RS-232 and passed it on to a T-modem, which was a high-speed intelligent radio modem, capable of 9600-b/s-data transmission using GMSK modulation.

At the office site, a T-modem received the data (converting the GMSK to RS-232) and passed it on to a channel in the FOS unit through the fibro cable to the network multiplexer into the RTS. There was a time update to the stations every five minutes. This network in June 1997 was upgraded to 2400 b/s.

No. 1 Shaft Vaal Reefs Seismic Sub-network

The No. 1 Shaft sub-network (Fig. 5.11) was a part of the Regional Klerksdorp Network. This sub-network consisted of only four stations with a multiplexer (the

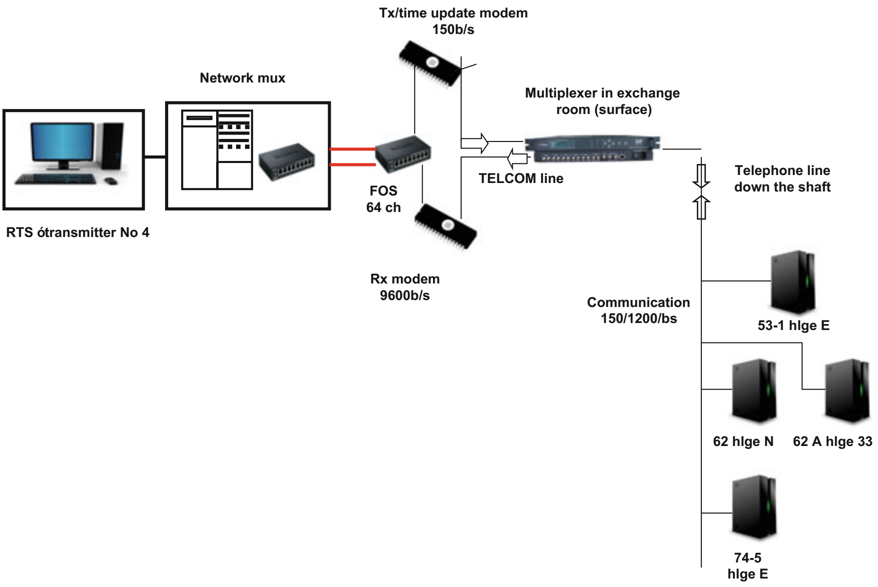


Fig. 5.11 No. 1 Shaft Vaal Reefs seismic sub-network

other two stations were in the Regional Seismic Network). The RTS communicated through the SCSI terminal server (serial port) to a line modem. This network used only one telephone line and no radio receivers or transmitters. The transmission from the modem to the multiplexer was the normal 150 b/s (FSK format). The data was then distributed to all the stations (PSs) via the multiplexer. From the stations, the data (FSK format) was passed to the multiplexer, which compressed the data onto a single line but at 9600 b/s. This was passed on to a receiving modem at the office side. The data was converted to RS-232 format by the modem and connected to a separate channel on the FOS unit. The received data flowed from the FOS unit via the network multiplexer to the RTS. The time update to the stations was transmitted every five minutes.

The No. 4 Shaft and No. 2 Shaft Hartebeestfonte in Sub-networks

With the experience from the previous three networks, it became clear that the data transmitted at 150 b/s was too slow for the number of stations linked to the RTS. The bottleneck of the system seemed to be the radios. With the modulation spacing of 12.5 kHz, a new modulation technique had to be implemented to achieve a higher transmission rate through the radio transmitters. It was decided to go for the FFSK (fast-frequency shift keying). The No. 4 Shaft Hartebeestfontein sub-network

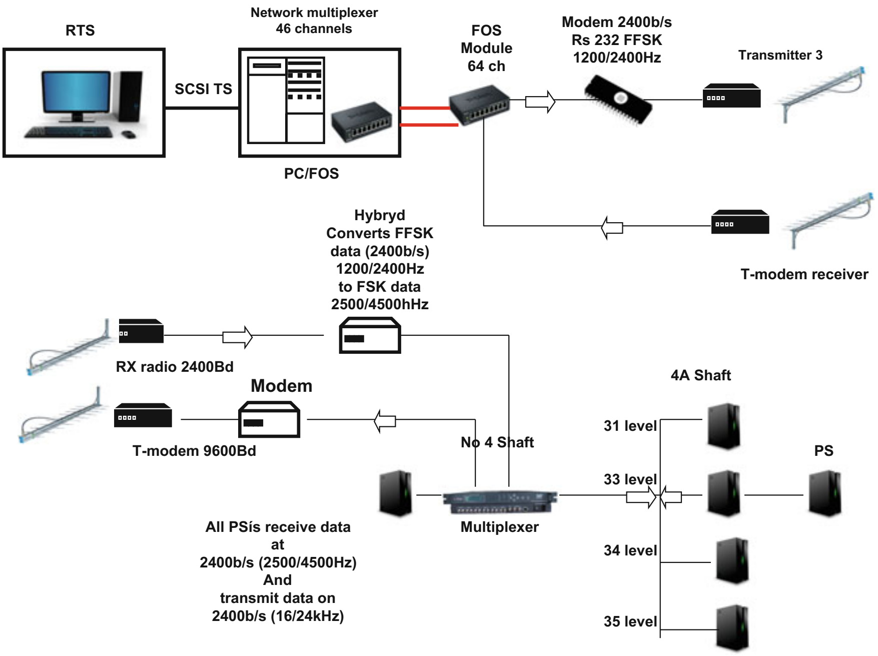


Fig. 5.12 No. 4 and No. 2 Shaft Hartebeestfontein sub-networks

(Fig. 5.12) was the first network to run on this new technology. If this technique would prove itself, it was planned that the Regional Klerksdorp Network would also be converted to 2400 b/s. The 5B sub-network at that time was in the process of being extended to 15 stations working on 2400 b/s from the RTS. Data was transmitted at 2400 b/s from the RTS through the SCSI terminal server to the network multiplexer to a FFSK modem (1200 and 2400 Hz) and then to a radio transmitter (3).

In the shaft area, a radio receiver received the incoming data from the RTS and channelled it to the hybrid. The hybrid converted the FFSK (1200 and 2400 Hz) data at 2400 b/s to FSK (2500 and 4500 Hz) data at 2400 b/s, and then sent it to the underground multiplexer. From the multiplexer, the data then passed to all the stations (MS) on a single telephone line. From the stations the data was transmitted at 2400 b/s (16,000 and 24,000 Hz) to the multiplexer. The multiplexer compressed the data to 9600 b/s and transmitted it to the T-Modem at the shaft headgear. At the central site, a T-Modem received the data, converted it to RS-232 format, and passed it on to the FOS unit, then to the network multiplexer on a separate channel. The time update was also sent every five minutes to the stations.

The No. 8 and No. 11 Shaft Vaal Reefs Sub-networks

The RTS sent the outgoing data to the network multiplexer via an optic cable. The network multiplexer consisted of a 486/33 MHz PC and three smaller FOS units. These FOS units communicated via separate fibre-optic cables (two pair per multiplexer) to the three multiplexers underground. From the multiplexers data was sent in FSK format at 9600 b/s to every outstation. Data from the stations was sent at 9600 b/s to the multiplexers. This data was then passed on to the network multiplexer and then to the RTS. To process the data from these networks, a fibre-optic link was used between No. 8 Shaft and the central site (Fig. 5.13).

The No. 2 Shaft Vaal Reefs Sub-network

This network (Fig. 5.14) had its own RTS on the shaft. For the processors to process the data, a radio LAN (microwave link) was installed on the shaft headgear. A fibre-optic cable and media converters between the headgear and RTS assured a one Mb/s data-transfer speed between the seismic offices and the RTS. The RTS on the shaft sent the data and time- update pulse (RS-232 150 b/s) via the serial port of the Silicon Graphics computer to a modem, which converted the RS-232 to FSK

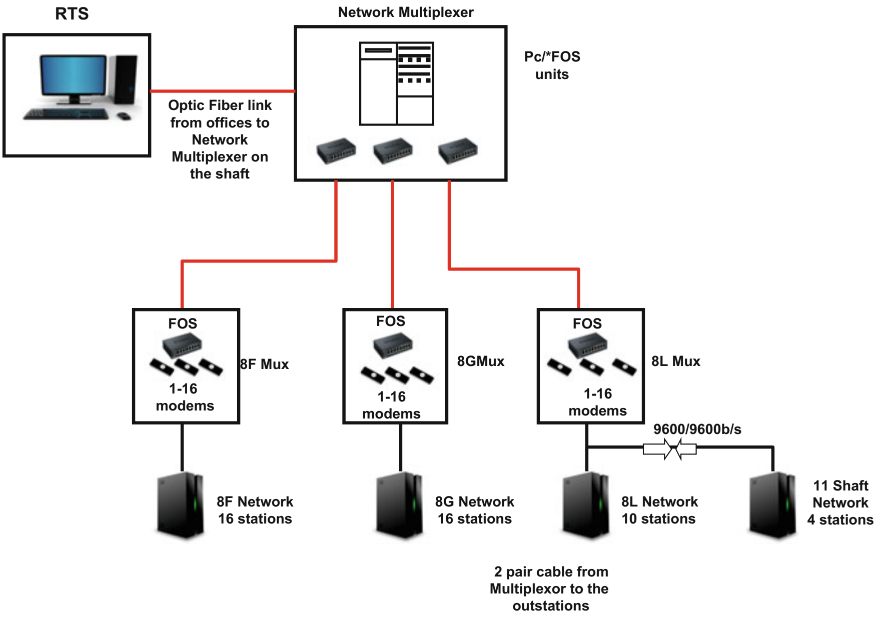


Fig. 5.13 No. 8 and No. 11 Vaal Reefs Shafts seismic networks

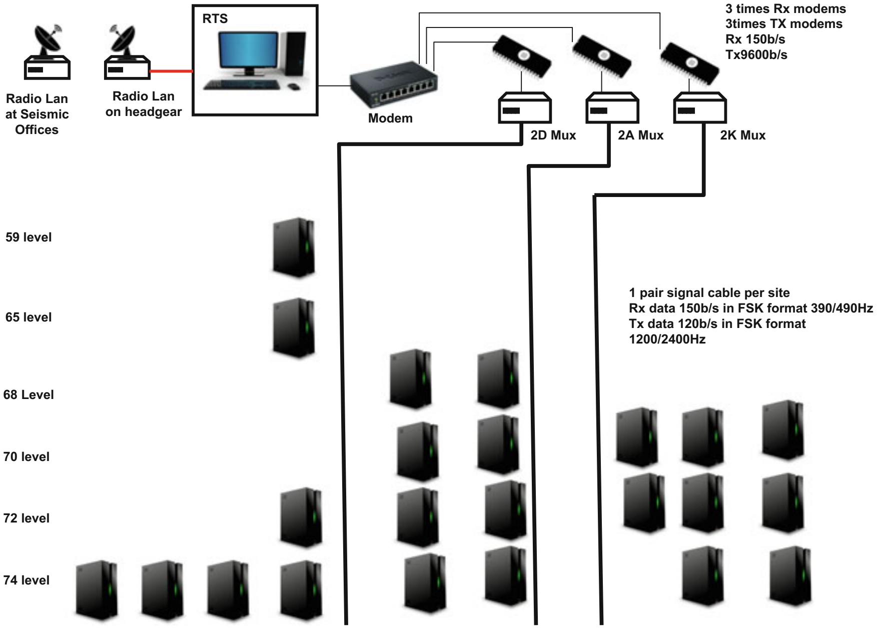


Fig. 5.14 No. 2 Shaft Vaal Reefs sub-network

format and passed the data on to the three multiplexers. The multiplexers passed all incoming data and time-update pulses to the stations. The stations sent their outgoing data at a rate of 1200 b/s also in FSK format to the multiplexers. The multiplexers compressed the received data to 9600 b/s and converted it to RS-232 format and then passed it on to the eight-channel SCSI terminal server. Each multiplexer used a separate channel. A 50-pair cable was installed down the shaft from the surface to the 74 level. At the time, it was planned to convert this network to 2400 b/s with a single multiplexer and 24 channels.

The No. 4 Shaft Vaal Reefs Sub-network

During the second half of 1997, this network (Fig. 5.15) was in the process of being installed. When completed, it would consist of eight stations and a RTS on the shaft. The data from the RTS would be transmitted through a radio LAN to the offices for processing. A high-speed, short-range modem (V.11 RS-422) would provide the data transfer between the RTS and the underground multiplexer. The data flow between the multiplexer and the stations could be either 2400 b/s for a single-pair cable or 9600 b/s for a two-pair cable installation. An optical fibre and media converters would be installed between the RTS and the shaft headgear, where the radio LAN would operate. The geophone boats would be equipped with SM14 (14 Hz) geophones.

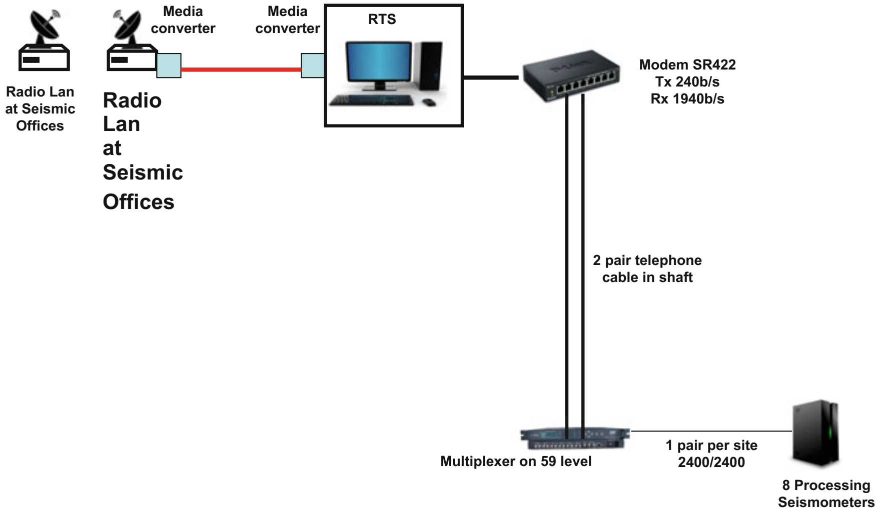


Fig. 5.15 No. 4 Shaft Vaal Reefs seismic network

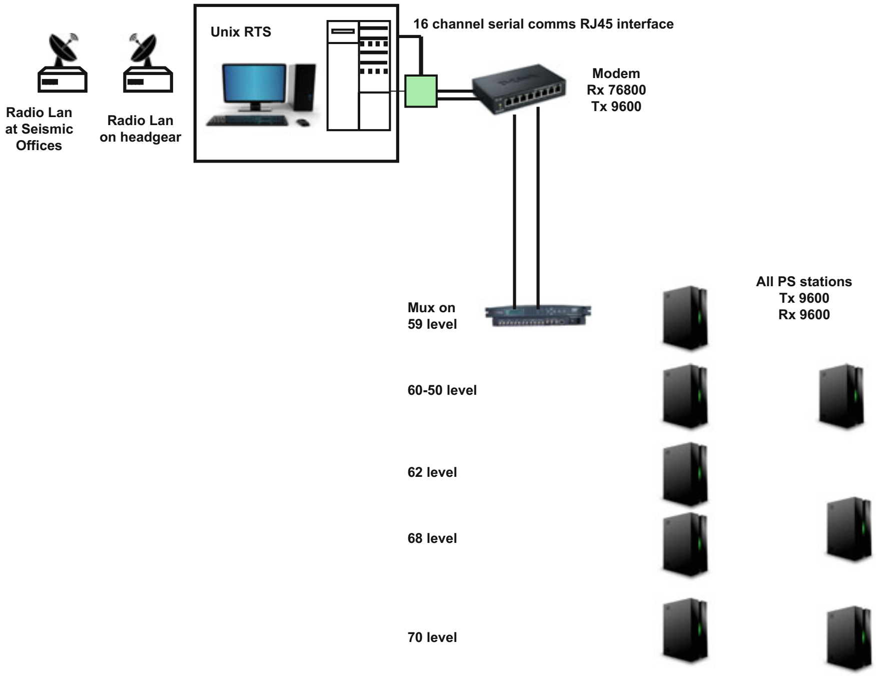


Fig. 5.16 No. 5 Shaft Vaal Reefs pillar seismic network

The No. 5 Shaft Vaal Reefs Pillar Network

A 16-port serial SCSI terminal server interfaced the RTS with a V.11/RS-422 modem. Data was sent from the RTS via the asynchronous V.11/RS-422 short-range modem to the multiplexer underground at a speed of 9600 b/s. With a two-pair signal cable from the multiplexer to an outstation, it was possible to send and receive the data at a rate of 9600 b/s. The processors accessed the data on the RTS through a radio LAN link. This network was generating its own time update (Fig. 5.16).

The No. 5 Shaft Vaal Reefs Upgraded Network

This network (Fig. 5.17) operated in the same way as the No. 2 Shaft and No. 4 Shaft Hartebeestfontein networks. The only difference between them was the data link from the multiplexer to the RTS. The stations received data at 2400 b/s and also transmitted data at 2400 b/s. A high-speed modem transmitted the data from the multiplexer to the RTS through five km of telephone lines.

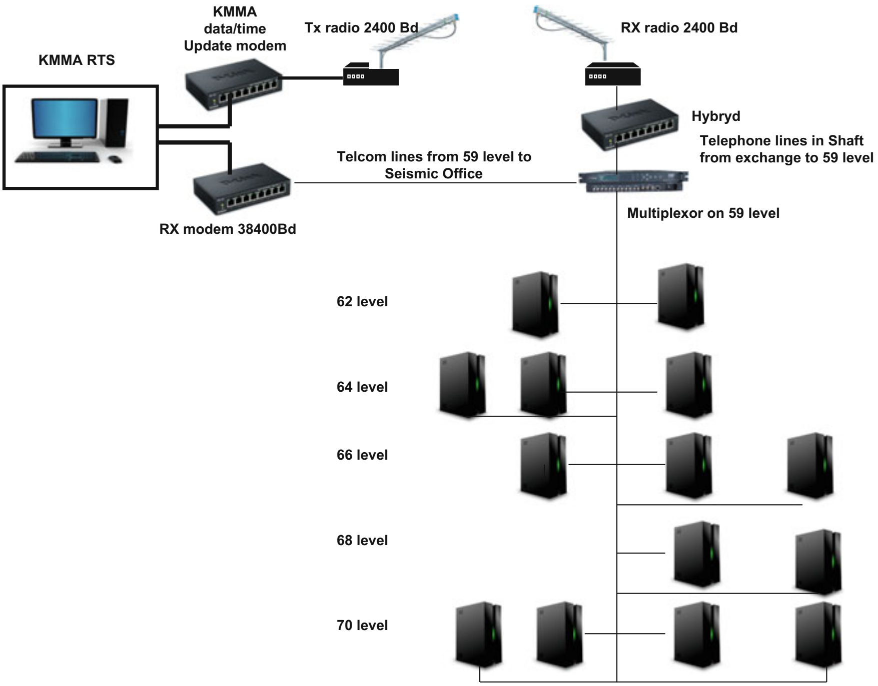


Fig. 5.17 Vaal Reefs No. 5 Shaft upgraded seismic network

Fig. 5.18 Surface site

KMMA Regional Seismic Network Surface Site

Figure 5.18 illustrates one of the surface geophone sites. These stations were located in the felt far away of any centres of human activity, even the smallest-possible ones. Once they were detected, they were vandalised on a regular basis. For this reason, we had to secure them as well as possible. Solar panels had to be installed on top of 12-m-high steel constructions. Still, the robbers would climb up them and take the panels. The next security upgrade would include anti-climber barbed wire on the poles. Still, some of the solar panels were stolen.

Chapter 6
What Happened After 1997?

By the end of 1997, the Klerksdorp Mine Managers Association (KMMA) Regional Centre was operating 127 seismic stations distributed over five separate networks. The original 30-station regional network evolved into a network of 75 stations distributed all over the Klerksdorp mining area, with a number of sub-networks in which the stations were concentrated at areas of intensive mining. There were also four other independent networks. In 1998, ARM (African Rainbow Mining) was formed and took over from AngloGold shafts, at which there were dense and modern networks. The K.M.M.A. Seismic Liaison Committee became the Seismic Network Management Committee. The ARM mine became the biggest contributor towards the working costs of the seismic central site. At this time, each mine had its own mine seismologist. The main purpose of the network was now only to supply them with quality seismic databases and continue with the 24-h monitoring and recording. Contacts between the network seismologist and the mine seismologist became very irregular. The mine seismologists became part of the mine rock engineering sections and reported directly to the rock engineering manager. In addition, there were numerous problems with the new version of software that was installed by the end of 1996. Those problems carried on for the next 12–14 months. Due to this, the seismic-warning method wasn't practically used for the whole of 1997. All seismic interpretations were of low quality. The seismologists had lost confidence of rock engineering and production personnel. Because of the new Health and Safety Act, the rock engineering staff concentrated their efforts on legal aspects, as well as on preparing the Code of Practice. By the end of 1997, new software had been installed and a time-and-effort-consuming process to recalculate all of the databases had started (as far back as 1990). This task was finally completed by the end of 1999, and, by this time, the KMMA Regional Seismic Network ceased to exist. By the end of 1999, AngloGold decided to pull out, and, as a result, each mine operated its own separate networks at the beginning of the year 2000.

S.N. Glazer, *Mine Seismology: Seismic Warning Concept*,
https://doi.org/10.1007/978-3-319-62353-5_6

6.1 Predictions, Alert, Alarm, Scram, and the Seismic Warming

“In the past there have been references to rock burst predictions. This was then changed to alert alarm and scram technology, and now we are moving with times being politically correct and referring to levels of warning.” This citation is from the keynote address given by Executive Officer Technology AngloGold when opening the SARES 1999 Symposium (Hodgson 1999). Why would he in one sentence mention prediction, alert, alarm, scram, and warning and connect these with politics? The answer is easy. As from about 1993, the gold industry of South Africa was full of confusion as to the role of mine seismology. Previously, its position was simple: it was there to monitor the seismic hazard and apply analysis results in order to improve the underground safety. Then, without prior announcement, very optimistic public statements were made in regards to predictions, for example, this one made by a top AngloGold manager: “Anglo American Corporation made it possible to anticipate seismically active and therefore dangerous areas and actually pull people out. And then” Mining World in May 1996 under the title “Seismic Monitoring Systems Saves Lives in S.A. Mines” among other sensational information stated: “The system has already been responsible for a number of accurate rock burst predictions which have saved lives… The first success for the ISS system came in May 1993 during a pilot surveillance project at Western Deep Levels. We were able to provide accurate warning 24 h in advance of a major magnitude 4.0 rock burst. Twenty miners were relocated out of the target area ahead of the event, and so no lives were endangered”. At that time I was working as a seismologist at Vaal Reefs, but I was not aware of such developments in mine seismology. Today, I believe that these tales about successful predictions were an unexpected result of SIMRAC. Safety in Mines Research Advisory Committee was created in 1993. At that time, rock-burst accidents in gold mines were one of the predominant reasons for accidents. This committee was using funds from the mining industry to sponsor research that should result in safer underground conditions. Mines were contributing with a levy whose size depended on safety, or rather, on mine-accident rates. According to Adams and van der Heever (2001), the SIMRAC budget (to the end of 2001) for research in rock engineering and mine seismology was 36-million US dollars. According to the same source at that time, there were 44 rock engineering projects in progress. Only these two figures indicate the amount of research taking place at the same time. With such volumes, its introduction into industry practice seems impossible. At the time, there were the following five research organisations that were engaged in rock-engineering and mine- seismology research based on funds from SIMRAC (Durrheim 2010):

1. MININGTEK: Chamber of Mines Research Organization (COMRO) merged with the Council for Scientific and Industrial Research (CSIR) in 1993, and the CSIR Division of Mining Technology (Miningtek) was formed with a staff complement of about 250. However, support for mining research continued to

decline. The CSIR Centre for Mining Innovation was established in 2009, with a research staff complement of about 40.

2. ISS International Ltd. (ISSI) , a company specializing in technologies to monitor and model the rock-mass response to mining, was founded in 1990. ISSI has conducted many research projects for mining companies and SIMRAC and took part in collaborative research programs.
3. Some research was performed by the Council for Geosciences, University of the Witwatersrand and SRK consulting.

The majority of the research in mine seismology was done by ISSI. Their fundamental research project GAP 017 (Mendecki 1995) was titled “Seismology for Rockburst Prevention, Control and Prediction”. This was a three-year contract that started in 1993 and ended in 1995. According to its authors “the primary output of the project “Seismology for Rockburst Prevention, Control and Prediction” was to develop methodologies for long-intermediate- and short-term rockburst prediction based on quantitative data provided by the modern seismic networks. The intention was that the developed methodology should be objective, i.e. based on sound physical principles rather than on loosely defined patterns or trends observed under certain circumstances, which are often strongly site dependent. Thus, investigation into “seismicity and geological features” or “seismicity and mine layout” was considered not entirely objective since there are no two identical geological features nor two identical mining and geological situations”.

If there are no two identical faults or dykes and there are no two identical combinations of geology and mining, then this means that mining-induced seismicity is not only induced by mining but it also depends on mining and geology. That is why there are no two seismic events that would be the same. This applies to all seismicity from the smallest to the largest sized. For this reason, every time-and-space series of seismicity will be different from any other one. This is bad news for those who want to predict seismic events, but it is good news for those who use or used recorded seismicity for monitoring the seismic hazard, or the mining progress. Examples of applications for monitoring hazard are given in Chap. 4 of this book. Most of these examples include descriptions of follow-up actions that resulted in increased safety standards. The application of recorded seismicity for monitoring the mining progress is described in Glazer (2016). In this case, recorded seismicity was used to monitor the caving-process progress.

It is interesting to note that GAP 017 project was audited by two authorities in rock engineering and mine seismology. Project GAP 345 titled “Audit of SIMRAC project GAP 017” was done by Spottiswoode (1997) and Project GAP 346 “Audit/review of project GAP 017” by Ortlepp (1997). All I wanted from these two projects is to make sure that my understanding of the basic idea behind project GAP 017 was correct. My understanding is that this project should introduce into mining the prediction of damaging events and that this prediction is the bona fide one because it will include place, time, and size.

From GAP 345: “The GAP017 project focused directly on predicting the time and place of impending rockbursts, on three time scales that are called *alert*, *alarm* and *scram*. The project aimed at using improved seismic systems, analysis methods and phenomenological models of rockmass behaviour for successful rockburst prediction”

From GAP 346: “The primary objectives are the development of strategies, methodologies and technologies for **proper** seismological monitoring, with appropriate analyses and interpretation, in rockburst-prone mines. (In this context, **proper** means producing data which is quantitative in terms of accepted physical parameters). The ultimate purpose of this endeavour would be to provide the means for guiding preventative and control measures employed on the mine and **predicting** rockbursts. Prediction can be taken to mean **where** and **when** damaging and potentially life-threatening seismic events can occur. The detailed procedures and methodologies that it was anticipated would be followed in the striving to achieve these objectives, were grouped into three sub-goals:

2.1.1 Rockburst Alert

The endeavour would be to detect zones in the rock mass **WHERE** potential for significant seismic activity is developing. The hope being that preventative action (layout, sequence, support) could be taken.

2.1.2 Rockburst Alarm

The endeavour would be to determine **WHEN** the build-up in activity could be close to ‘instability’. The intention would then be to ‘defuse’ the threatened danger by triggering through a special blasting procedure or to reduce the risk by improving control measures e.g. increasing the quality of support or reducing exposure of personnel (e.g. Preventing entry of the night shift).

2.1.3 Rockburst Scram

The hope expressed implicitly here is that the beginning of self-nucleation of rockbursts (onset of instability) might be detected so that the evacuation of people from specific areas could be initiated.”

From this excerpt, the aim of the project “Seismology for Rockburst Prevention, Control and Prediction” is clear and very specific. It is about predicting damaging seismicity in the mining environment. This prediction includes not only place but time and, to some extent, it must include size because there is no sense in predicting small-sized events. In general, results of project GAP 017 were seen as positive, and the general comments at least in writing were encouraging further research into prediction. From Adams and van der Heever (2001):” SIMRAC has directed research towards understanding the instability of the rock mass project GAP017 developed a method for the quantification of the rock mass response to mining in space and time. New seismic parameters have been defined to quantify rock failure. For example, the research showed that in some instances, an increase in the cumulative apparent volume ΣV_A and decrease in the average energy index EI occurred before instability. A procedure to quantify the potential for instability in terms of "time failure" has been defined and tested. Chaos theory has been applied in the attempt to predict seismic activity from few hours to three weeks before the event. It is suggested that the success depends on the seismic network sensitivity and the real-time computing power available".

Consequently, there was more research dedicated to mine seismology, for example, project GAP211 Dzhafarov, ISSI (1998) "Non-linear seismology". This project was about the processing of data recorded close to the seismic source. This is continuation of the prediction research as that to be correct and reliable requires operation of dense and very sensitive seismic networks. This is the academic point of view. The problem is that these super-networks have to be installed and then maintained by the mines. Then there was project GAP 409 de Beer, ISSI (2000) "Seismology for rockburst prediction". This project as a main output presented a method for predicting larger mining induced seismic events in gold mines. In Introduction author of this project makes the following observation: "To date, prediction has been practised by very few people in the South African mining industry for two main reasons:

1. **The ostrich mentality: avoidance of the facts**. Prediction is a politically and economically risky issue, since the fact that precursory patterns exist creates high expectations from official, public and labour quarters. False alarms and failures to predict therefore carries a high cost in terms of trust and damages. Better to avoid the issue, sweep facts under the carpet and sit out repeated inquiries where precursory patterns are retrospectively pointed out.
2. **The *Windows* mentality: point and click**. To learn to recognise precursory patterns takes a long time and involves a lot of painstaking effort. Application of this learned intuition time and again, in an iterative process, without getting distracted by initial failures, takes a lot of energy and commitment. Better to say that in the modern fast business environment it is unreasonable to expect anything unless it can be created by pointing a mouse and clicking for an answer".

Well, as research is about understanding (not believing), so is its implementation done in practice. I have done in practice something probably second to predicting. I have practiced issuing seismic warnings. I could do it only when there was good understanding what seismic warnings are about. This understanding was between the seismologist, rock engineering staff, and mine management. What's more, at that time, I was satisfied even more when there was no damaging event as expected and the mine increased their support standards. This was not only my attitude. Forget about being happy when the prediction was right or about listing on the office wall the names of those that were evacuated and so escaped injury or death

The second important fact is that the industry does not have, or cannot afford staff, to take on such implementation processes that require time, energy, and commitment. The reality is that running a network usually is not the only job of the person put in charge of the seismic system.

At this stage, I don't want to go into speculation about whether research financially supported by the mining industry into prediction techniques is correct or not. Let's at this stage assume that the research ends with some results that then have to be implemented in the industry. This means that now the industry has to spend even more not only on the seismic system but on very specialized high-class experts. Such specialists at the time were not available. If there were some capable and available individuals, then they probably were not ready to work at the mine. This applies to the years of 1990–2000 and probably is still a correct assumption at present (2017). The need for specialists would become a problem assuming that the industry would be willing to apply the research results. According to van der Heever (2002): "The main barriers to successful transfer that have been identified can be summarized as follows:

1. During the first few years following its inception, SIMRAC did not appreciate the need to have a formal dedicated technology transfer strategy as communication and publication of research results were deemed adequate. The onus was placed on mines to act on recommendations.
2. SIMRAC did not plan nor allocate funding for the dissemination and publication of research results and assumed that the assimilation of changes in technology would result from technology-pull by mines.
3. Because of their non-involvement and non-ownership of projects, end-users are not convinced that the adoption of new technology would be beneficial.
4. The majority of mines do not possess the organizational culture, skills and procedures to utilize new technology. Planning and budgeting for new implementation of new technology are therefore seldom formalized".

This list could be longer, but I think that point four, unfortunately, is very true. There are not many decision-making managers in the industry who are interested in applications of new technology. Today, they do not need mining experience to manage the mine, so they depend on technical staff to advice on technical matters. Junior managers have too much on their plates to think about new technology.

I retired in 2013 from being active as a mine seismologist. Especially during the last ten years, I attended a number of rock engineering conferences and studied and listened to a number of presentations. I have travelled to many mines as a consultant and have met a lot of specialists working in the mines. Being retired, I am still interested in mine seismology and would like to read about its progress and new applications in the mines. There is a lot of data to study, but there is not a single one claiming successful prediction. In a way, the subject of prediction can be found in Spottiswoode (2000), where the conclusion is that prediction is not possible. It might be possible to forecast larger-sized seismicity. It seems that, by the end of the previous century, prediction in mines popped up by chance and then disappeared back into the abyss. Some might claim that it resulted in a lot of useful research output, but I do not agree with this argument. Yes, many man-hours went into this research, but it was tunnelled only with the aim of predicting. For this reason, for example, the so-called all-new seismicity parameters have no other application than prediction. So with no prediction, they are of no further use. Before prediction came into mining, it was present in global seismology. There, it also claimed many man-hours for new developments (hopes), but in the end it was decided that it is impossible to predict now and or in the future with the so-called new developments in this area. “The popular belief that earthquakes are predictable is in odds with correct research. At the recent RAS-JAG (Royal Astronomical Society—Joint Association for Geophysics) discussion meeting, “Assessment of schemes for earthquake prediction” (London, 7–8 November 1996), the clear consensus was that individual earthquakes are inherently unpredictable because of the chaotic, highly nonlinear nature of the source process. The earth appears to be in state of “self-organised criticality”—always teetering on the edge of instability. Exactly when and where earthquakes occur, and how large they will grow after they start, depends on a myriad of fine and immeasurable details of the physical state of the earth over a large volume, not just the immediate vicinity of the fault. The idea that the earth telegraphs its punches, i.e., that large earthquakes are preceded by observable and identifiable precursors like many such “obvious” ideas, isn’t backed by facts” (Geller 1997).

So, there goes prediction with its concept of alert, alarm, and scram as politically incorrect and now what about the politically correct (in the year 2000) concept of seismic warning. And, what about the politically correct “levels of warnings”? What is a warning, and can it be divided into levels? The Oxford English Dictionary gives the following meanings for “warn”:

- To give timely notice to (a person) of impending danger or misfortune
- To put (a person) on his guard, to caution against some person or thing as dangerous
- To give (a person) cautionary notice or advice with regard to actions or conduct
- To inform, notify, to notify of something requiring attention

The same source explains that “warning” means the following:

- Taking heed, precaution
- Advice to beware of a person or thing
- Cautionary advice against imprudent or vicious action

The phrase “to take warning” means “to alter one’s course of action when warned of the danger”. The only references to time is to “give the warning in time”, that is, before the danger can take place, not after. Levels of warning imply, by definition, the use of a quantitative technique, which is not the case in practice, at least in mine seismology. The idea of warning levels is used in the military by their “army intelligence”. The army developed several warning systems because of the importance in their tactics of surprise, timing, and place of attack, routes, and types of weapons or strength of the enemy. A long-term or political warning system employs diplomatic, political, technological and economic indicators to forecast hostilities. Strategic or medium-term warning involving a time span of a few days or weeks is a notification or judgement that an attack may be expected. Short-term or tactical warning often hours or minutes in advance is a notification that the enemy already has initiated hostilities. According to the above definitions: In a seismically active mine, the long-term warning is always in place, as it is reasonable to expect that sooner or later a seismic event will take place. For this reason, the mining industry has in place several defensive tactics. A medium-term (days or weeks) warning is in fact only a notification or judgement that a seismic event might be expected. Still, its exact place, size, or timing remains unknown. The military, in such cases, goes into action by taking various preparations against an expected attack, but they can do only what a reasonable commander would deem practical and advisable in a given situation. They probably have several scenarios of action to be taken after opening the envelope with the magic "Top-secret" label. Military short-term warning would in seismological terms mean that the event is already taking place and no action against it can be taken. One could argue that, before the main attack, there are certain other indicators of hostilities that can be detected. This is true, but it does not apply to a seismic warning. There are no seismic precursors as preparatory time and actions that must take place before an offensive. On the other hand, the military uses a number of detection systems of which acoustic sensing is only one. It is used to detect movements of people or vehicles by sensing vibrations in the ground. Other methods like infrared, radar, radio sensors, sonar, magnetic, nuclear, chemical, and direct visual observation supplement this method. These methods are used on land, air, or sea employing various carriers. Looking into the history of war, one can find a number of successful military surprises against which warning systems were helpless. For example, there was the destruction on 7th December 1941 of the United States Pacific Fleet at Pearl Harbour by surprise Japanese air attack. The other successful military attack that comes to mind due to it size is the German invasion of the Soviet Union in June 1941. Earlier, there was a successful German invasion of France that went around the Maginot Line. The military, possessing the manpower, science, and unlimited financial resources, have not been able to develop an ultimate warning system. So how can a mine seismologist, with only one type of detector, be expected to achieve even more? There is still one more very important disadvantage in the seismic-warning system. Very often it is compared with weather forecasting. The latter is based on sound principles of physics. "In the turbulent motion of fluids, the fluid properties are known. However the reliable prediction of air motion in a room can be calculated only for a few minutes, and Earth's atmosphere circulation can be predicted for a few days when inertial effects are strong. For earthquakes the inertial effects are strong only during earthquake rupture and subsequent seismic wave propagation-seconds" (Kagan 1997).

Observations of synoptic systems resulted in expanded knowledge about the basic physics of the three-dimensional rotating fluid, such as the atmosphere. This led to attempts to forecast the weather for a few days or even a few weeks by applying this knowledge to an initial observed state of the atmosphere. Forecasting relay on increasingly more sophisticated mathematical models, constructed with the aid of modern computers. This resulted in relatively accurate forecasts for up to 72 h. Attempts to forecast the weather a few months in advance have only limited success. Such long-range forecasts are very difficult because individual synoptic systems, such as cyclones and anti-cyclones with their troughs and ridges, have a life cycle lasting only 3–7 days. "While the most violent manifestation of the atmospheric turbulence, a tornado can be predicted with a lead time on the order of half an hour with few errors, a catastrophic earthquake may occur practically without warning. However, the prediction of a tornado's path, as well as that of a tropical hurricane, faces serious difficulties, since small variations of initial conditions may drastically change its trajectory" (Kagan 1997). The weatherman has at his disposal measurements such as temperature, pressure, and wind direction and speed on a three dimensional grid. The mine seismologist, on the other hand, has no such measurements. All he has are the estimates of the source parameters.

6.2 Applied Mine Seismology: A Vaal Reefs' Perspective up to 1997

Now we return to the times when prediction with its alert/alarm scram was still politically correct. The first seismic warning at No. 5 Shaft Vaal Reefs was given at the end of October 1994. It is my experience that the decision-making mine management valued them as a tool that could that could be used to increase the level of underground safety. Direct proof of this was not only the large amount of capital spent on installing and developing the underground seismic monitoring systems, but also on personnel that operated these systems and had knowledge of seismology. At the beginning of the warning experiment at No. 5 Shaft, V.R., the seismologist involved, issued several warnings for places that were located outside this area. There were also cases of reporting seismic warning that were based on very limited and on not so obvious trends. In many cases, it was difficult to make a decision. On the one hand, giving a warning could result in saving lives, while, on the other hand, issuing a warning, especially for areas with insufficient seismic cover, could jeopardize implementation of the concept that had already been proven to work in the experimental area. This was, at the time, seen as a high risk, as further implementation was dependent on results. This was not an easy problem to solve. In July 1995, the mine seismologist (that was I) received, from the decision-making management, very clear instructions as to the matter of issuing seismic warnings (see Sect. 4.5.4). This decision was made when, at the time, a procedure was in place to be followed when areas of potential instabilities had been identifies. From the seven warning issued from the end of October 1994 to the end of December 1994, four ended in events of local magnitude above 2.5, and, in two cases, the underground working places were found to be too dangerous to continue to mine. As a result, they were abandoned. With one warning still in place, it became clear that a procedure for handling this type of information had to be formulated. Such a procedure had to have two separate elements. The first was the way of passing down the information, and the second was how to describe actions to be taken by those responsible for safety and mining. By January 1995, when instability was detected, the seismologist would discuss it with the rock mechanic working in the area. He would then report it to the section head while still involving the seismologist. Then the rock mechanic would contact the section manager and give him a copy of the seismic data—usually in form of a time plot. No formal report was prepared at this stage. It was understood that the section manager would then make decisions as far as safety was concerned. By February 1995, mine management approved a follow-up procedure that is cited in Sect. 4.3. This procedure was still in place at the end of 1997. It is interesting to note that this instruction used a phrase "areas of concern" for the polygon in which the instability was identified, and that it did not make an issue out of the timing of the expected event. All action that was requested was to make sure that all normal requirements were already in place. All three parties (seismologist, rock engineer, and mining personnel) were convinced that seismic warning as such had a great and positive impact on improving underground safety. I have already mentioned the phrase "area of concern" that was used together with such terminology as prediction, instability, alert, etc. At the time, this was not of major importance because all energy was focussed on practical aspects of what was going on. The other factor at that time was that the method was limited only to part of one shaft. It is probably important to mention that all individuals involved were, at the time, very "pro-seismic", and there were no legal requirements in place to use the method. The general feeling was that being proactive was the right thing to do. A good example is a seismic warning given on 11 May 1995 (seven months into the experiment) regarding an area located outside the experimental network. The scrutiny of plans and knowledge of the area indicated that all panels in the section were mined in proper sequence and that all of them had second escape ways in place that were clear. The already existing recommendation to use two rows of hydraulic props with headboards in every working place was the only outstanding problem and was not yet fulfilled. This recommendation at the time wasn't implemented due to a shortage of props. Action to overcome this problem became a priority. An underground inspection within the next few days was to take place to ensure that the recommended support was in place. This warning was then cancelled. The warning of the 11 May 1995 was based on a limited amount of data. Small seismic events recorded between 11 and 20th May 1995 indicated that there was no instability in the area. The follow-up actions that were taken improved the underground-safety standards and were therefore not a wasted effort from the point of view of the mining personnel. The "unsuccessful" warning did not lower the confidence in the method. It is important to note that already at this early stage of the experiment Vaal Reefs Mine adopted a philosophy that the success rate should be measured in preventative actions taken, rather than in the success of the predictions themselves.

This was a great psychological break-through. Up to that date, every seismologist's dream was to predict and be right. Now it has changed to the opposite because we hoped to be wrong, and, if the event took place in an area where the standards were in place due to the warning, with no fatal consequences, then the general feeling was that the method was working and thus a success. A typical example of the above is a seismic warning dated 2 January 1996. This warning was given based on good quality indicators. Two weeks later, an event of $M_L = 2.3$ occurred in the expected area. Due to support being up to standard, it resulted in only slight damage (centre gully packs kicked out) with no consequences to people or production. It is easy to count the losses due to bad mining practices, but it is practically impossible to do such a count in the opposite situation—how many lives were spared and how much production was gained by compliance with good mining practices. Having statistics on the latter would be the ultimate proof that the seismic-warning system had strong and direct impact on safety improvement. The impact of the introduction of the instability (warning) concept in the experimental area of No. 5 Shaft is difficult to quantify, as there were relatively few accidents that related directly to specific seismic events in 1995. Accidents often occur due to the damage caused by a seismic event or work done related to the repair of seismic damage. For this reason, the general trend of the accident statistics for the whole shaft might be used as an indication of the success rate of the instability concept. The year 1995 is a good one for such estimation. A warning system was in use for the whole year, and in the area of interest there were 36 potentially damaging events. In the first quarter of 1995, the reportable accident rate was at the level of 45, and it then systematically dropped every quarter down to below 20 for the fourth quarter of 1995 (Nicolau 1996). Such observations were the reasons that the decision-making mine management decided to make more capital available and to install more similar networks. When I applied for more capital or an increase in the working budget, I always received the required capital, and it was then never reversed or cut due to financial problems. There were at the time some capital projects that were put on hold or cut down in size. 1996 was the year that the Mine Health and Safety Act was passed. Each mine then had to prepare the Code of Practice to Combat Rockfall and Rockburst Accidents (COP) by the end of July 1997. The intention of the act was to improve the safety.

6.2.1 *The Influence of the Mine Health and Safety Act and the Code of Practice*

I have found it enlightening to study the Code of Practice (COP). It made it easy to understand the gradual change of the attitude of the Vaal Reefs' rock engineers towards the seismic-warning method. The first clue in understanding this process is the following sentence from the Vaal River Operations Code of Practice. (Revision 2, dated 4 September 1998):

> It should be noted that the Code of Practice is a legal document, and it is an offence for any person(s) not to comply with all aspects. It should be further noted that all managerial and supervisory instructions, recommended policies, procedures and standards on any relevant topic, must comply with the content of the Code of Practice.

How does the COP address the problem of seismicity? Paragraph 1.6 of the Code of Practice-Mine Seismicity: "Major seismic events on the Mine are usually related to geological features. Using the high-quality digital data from the Klerksdorp Mine Managers Association (KMMA) Seismic Network, the following numbers of events has been recorded (Table 6.1).

It should be noted that the number of smaller events recorded has increased with time because the sensitivity of the system has improved with the increase in the number of geophones. Data presented by Table 6.2 is based on the local seismological relationship between magnitude and peak-ground velocity (PGV).

In the period from 1993 up to the end of 1997, only six events with magnitudes greater than 4.0 have been recorded. Underground stope-support design was based on these measured peak ground velocities (PGV), and a maximum value of 2.3 m/s is currently used. It is known that the PGV may be locally amplified in fractured rock, and this amplification factor is the subject of ongoing research, sponsored by SIMRAC (Safety in Mines Research Advisory Committee). It must also be noted that the rock around a geophone is also probably fractured to a certain degree, and, hence, the recorded PGV's are already possibly amplified (above those in solid rock). History has, however, shown that the current stope support used in seismically prone areas is basically acceptable, as far as rapid-yield ability is concerned. In effect, the PRS (Panel Rate System) takes account of the rapidly diminishing PGV with distance from the source. This means that panels closer to faults and dykes are at high risk of damage, and those further away are at lower risk. Seismic data is also

Table 6.1 Number of seismic events

Year	Event magnitude				
	Below 1.0	1.0–2.0	2.0–3.0	3.0–4.0	Above 4.0
1992	2179	1219	382	65	0
1993	3291	1039	280	41	2
1994	4399	1109	300	45	0
1995	14,357	991	226	31	1
1996	15,600	829	205	34	1
1997	6663	687	139	18	2

Table 6.2 PGV as a function of distance and magnitude

Distance (m)	Local magnitude			
	0.5–1.5	1.7–2.3	2.8–3.2	3.8–4.1
100	2.7 mm/s	2.6 cm/s	24.4 cm/s	2.3 m/s
200	1.0 mm/s	1.0 cm/s	9.5 cm/s	0.9 m/s
300	0.3 mm/s	0.3 cm/s	2.7 cm/s	0.3 m/s

used to determine the relationship between mining-induced seismicity and trends across boundaries, as well as the changes with time of day. These hazard and risk assessments may be used in consideration of centralised blasting and the validity of multi-shift of continuous stoping in certain areas".

My comment: "Data and interpretation easy to handle": PGV data was used in practice beginning in 1991 and was one of the first results of implementation of the digital seismic system in the area. It is also interesting take note of the phrase "trends across boundaries". Monitoring such trends was always one of the reasons of having a regional type of a seismic network.

Paragraph 2 of Code of Practice titled: Mine Rockfall and Rockburst Accident Analysis reads: "The historical accident analysis is the basis of judging the effectiveness of a rock related Code of Practice, and helps to focus on the most critical aspects that need attention and improvement". Only the sizes of fall out could be assessed. Whilst not all accident data could be found, a concerted effort had been made in that records of the mine, the AngloGold Head Office, and the Inspector of Mines were searched. Furthermore, the data was not sufficient to indicate a hazard, and thus a separate hazard assessment was required. Such a hazard-and-risk assessment study is being executed by the Mines' Environmental, Safety and Health Department. The results will be incorporated into a future revision of this COP as well as in the design of mine layout and support where possible and required. Table 6.3 list the rock related fatalities for time period 1990–1997.

The fatality data clearly show that the main rock-related problem is associated with falls of ground. The data does not reflect on the quality of standards employed in the accident sites. This approach is, therefore, highly conservative".

My comment: Table 6.3 lists rock related fatal accidents per year from 1990 to 1997. It is interesting to convert this data into a different format, as the values given are not related to production or the number of workers. The following is the result (Table 6.4).

Figures 6.1 and 6.2 illustrate data presented by Table 6.4. Two major trends can be noted: In general, there are three times more fatal accidents due to falls of ground

Table 6.3 Rock-related fatal accidents per year

Year	Rock related fatally	Fall of ground	Seismic
1990	44	25	19
1991	32	24	8
1992	38	25	13
1993	31	23	8
1994	25	17	8
1995	25	23	2
1996	29	22	7
1997	15	12	3
Total	239	171	68
Percentage of total	100	72	28

Table 6.4 Yearly percentages of rock-related fatal accidents

Year	Percentage of fatalities	Percentage of fall of ground (FOG)	Percentage of seismic
1990	100	57	43
1991	100	75	25
1992	100	66	34
1993	100	74	26
1994	100	68	32
1995	100	92	8
1996	100	75	15
1997	100	80	20

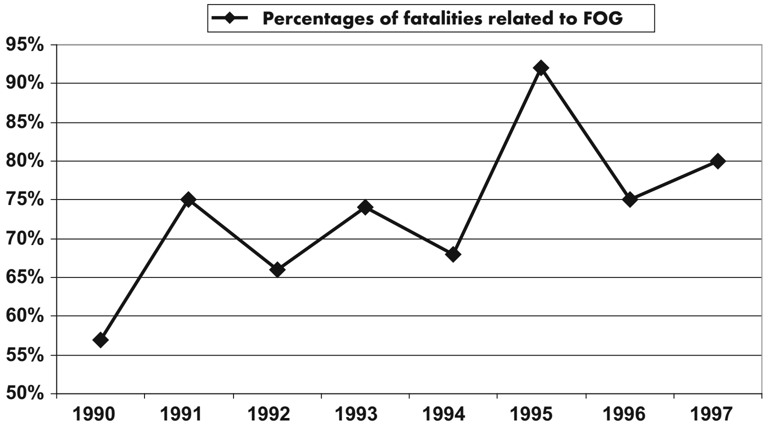


Fig. 6.1 Percentages of fatalities per year related to FOG

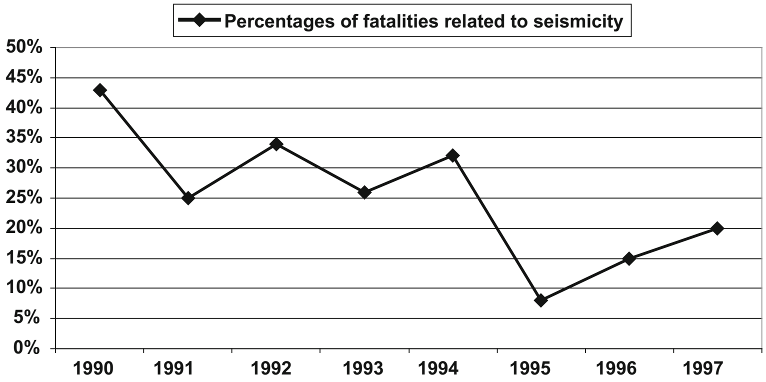


Fig. 6.2 Percentages of fatalities related to seismicity

than the rock bursts. The general trend of fatalities due to falls of ground has increased year by year, while the one describing fatalities due to seismic events, have decreased and are below the mean value as measured from 1995. This cannot be merely a coincidence, as those statistics according to COP still include the most seismically active areas, that is, presently Nos. 2 and 5 Shafts of ARM. It is also worth mentioning that the end of 1996 and the whole of 1997 were disappointing years for seismic warning, due to serious problems with the software. There was practically very little success to note. It cannot be a coincidence therefore, that there is a clear upward trend for those years.

From Paragraph 2.2 of the Code of Practice titled: "Rock Related Reportable Accidents": Detailed reportable accident data has been kept on the Mine from 1994. Table 6.5 summarises results from 1994: The results show an encouraging downward trend overall, and it can be seen that the main problem area is falls of ground.

From Paragraph 2.3 Code of Practice titled "Rock Related Disabling Accidents": Detailed disabling accident data has been kept on the mine from 1994. Table 6.6 displays the results from 1994.

The results also show an encouraging downward trend overall, and it is evident that falls of ground are the main problem area.

My comment: since the data from the last two tables is not related to production or numbers of workers, then the following should better illustrate the reality (see Tables 6.7 and 6.8).

Table 6.5 Rock-related reportable accidents

Year	Total	Fall of ground	Seismic
1994	406	347	59
1995	331	302	29
1996	293	252	41
1997	232	201	31
Total	1262	1102	160
Percentages of total	100	87	13

Table 6.6 Rock-related disabling accidents

Year	Total	Falls of ground	Seismic events
1994	710	616	94
1995	585	545	40
1996	561	484	77
1997	421	386	35
Total	2277	2031	246
Percentages of total	100	89	11

Table 6.7 Rock-related reportable accidents

Year	Percentage of fatalities	Percentage of fatalities associated with FOG	Percentage of fatalities associated with seismicity
1994	100	85	15
1995	100	91	9
1996	100	86	14
1997	100	86	14

Table 6.8 Rock-related disabling accidents

Year	Percentage of fatalities	Percentage of fatalities associated with FOG	Percentage of fatalities associated with seismicity
1994	100	87	13
1995	100	93	7
1996	100	86	14
1997	100	91	8

As the number of accidents is in the hundreds, even if the data is available only for four consecutive years, the following is evident:

1. In general, the accidents related to seismic events are a factor of seven lower that those related to falls of ground.
2. The trend stays the same for the four years.
3. There is a drop in percentage of seismic-related accidents for 1995.

The above statistics are alarming, and indicate a serious problem with falls of ground.

From Paragraph 3 of the Code of Practice titled “Rock Related Risk Management”: “Risk Management is a critical aspect in rock related safety due mainly to the difficulty of underground hazard identification by production personnel.” And “Risk Management in the field of rock engineering is generally covered by among other Monitoring (particularly seismic)”.

From Paragraph 4: Code of Practice titled:” Strategies to Reduce and Manage Rock Related Risks Influence on Neighbouring Mines”: Effects of neighbouring mines are considered through communication of rock engineering staff, seismic monitoring, and a (Seismic) Liaison Committee on Rock Engineering.

6.3 Rock-Burst Control Strategies

This subparagraph text is as it was in the Code of Practice: “As a direct result of the ever-increasing depth of mining the Klerksdorp mining district, a permanent seismic network was established by the Chamber of Mines in the area in 1971. The initial aim of the system was to locate seismic events in time and space. This limited data was used to delineate areas of higher seismicity and assist in focussing rescue operations after a major rock burst. In 1989 it was accepted that the Regional Seismic Network (covering Vaal River Operations, Hartebeesfontein, Stilfontein and Buffelsfontein Gold Mines), administered by the local Klerksdorp Mine Managers Association, had severe limitations as it was analogue based. In 1990, the system was replaced by a faster and more efficient digital system, consisting of 30 geophone stations of which 14 were located on AngloGold Limited—Vaal River Operations. This system not only provided rapid location and magnitude but also other physical parameters (seismic moment (Nm), radiated energy (J) size of event (m) stress drop (Pa). The development of the apparent stress concept was extremely useful. In the past, no correlation could be established between the magnitude of an event and the resultant damage. It was found that events of the same (or similar) magnitude had a very large range of apparent stress drop and the stress drop correlated well with the observed damage. Seismic monitoring could now become proactive and assist in not only identifying areas more prone to rock burst damage, but also to measure peak ground velocities. In 1991 the concept of apparent stress or energy index was developed and implemented experimentally on the mine. These indices relate the energy (apparent stress) of an event to the average energy (apparent stress) for a given moment. This concept is hoped to be used in the risk assessment process. In early 1993, gold mines administered by Anglo American Corporation formalised a strategy for seismic monitoring and rock bust control called the Alert, Alarm and Scram concept. Much of the research into the concept was funded by the Safety in Mines Research Advisory Committee (SIMRAC), and it was all undertaken by ISS International".

6.3.1 Seismic Monitoring Strategy

"AngloGold Limited—Vaal River Operations developed a 5 year plan in 1994 to lend focus to the important field of seismic monitoring to enhance seismic prediction, prevention and control".

6.3.2 Short-Term Plan 1994–1995

"This plan aimed to introduce the alert concept in the 5B, 2K and 8L mining areas in installing more geophones and purchasing the necessary hardware and software. The training of personnel in the relevant seismic skills was also a requirement".

6.3.3 Long-Term Plan 1996–1998

"The aims of the long-term plan, which is roughly halfway to date, were:

1. Implement best seismic monitoring parameters and strategy for the Mine
2. Improve the seismic accuracy by installing more stations where needed
3. Upgrade the seismic outstations
4. Upgrade the data storage, interpretation and transmission facilities
5. Introduce the instability concept relative to its applicability in all working areas that need it

The long term plan will be met, based on progress to date and availability of skills. The stability assessments however are still in the research state and it is unclear whether prediction per se will ever be possible".

6.3.4 Present Rock-Burst and Damage-Control Strategy

"Given the endeavours as well as the limitations in the strategy is to continue selection and testing of appropriate techniques. While the limitations may now allow "Alert" level strategies by definition, in practice all the "Alert" level strategies are considered should indications of exceptional seismic trends become known. Any reasonable information acquired regarding exceptional seismic trends will be considered as possible preventive measurements. Present use includes identification of active structures, migration of seismic activity, effectiveness of control measures like bracket pillars, monitoring effect of multi-blast or full calendar operations. Damage control is exercised through the Panel Rating System and associated support standards adopted to cater for expected conditions. Training in support types used is done by the suppliers and through the individual mines training systems. Other measures are training in the rock engineering for mining staff courses presented by AngloGold training system".

My comment: It is interesting to note that the seismologist wasn't included in the committee that prepared this COP. From this, it might be concluded that the above was only from the point of view of the rock-engineering practitioners, using selected seismological references as backup. From the whole paragraph, the following sentence needs some comment and attention: "The stability assessments however are still in research state and it is unclear whether prediction per se will ever be possible". Stability or the warning method had already been in use in this mine for over four years with some success, at least from the point of view of the mine management and production personnel. The clue words are "research state" and will come back again and again over the next two years. It is safe from the practical point of view to declare something like seismic warming to be in such state. The same applies to "exceptional seismic trends" because no one can define such a phenomena.

6.4 Code of Practice Research and Development Considerations

"Rock-burst control on AngloGold Limited—Vaal River Operations is based on ultimate concept of: ALERT, ALARM AND SCRAM. Although not totally developed and still in the testing stage, the concept is proving encouraging".

Alert: Where the seismic sensitivity permits, the mine is divided into numerous polygons representing discrete mining areas. An alert in an area should be identified because seismic activity is increasing, and the stress is decreasing whilst the strain rate is increasing. The time period is weeks or months and adequate time is available to consider practicability or preventative measures such as:

Ensure appropriate support standards are in place
Search for, identify, and treat areas of potentially poor site response
Changes in the mining layout (such as leaving strategic pillars)
Altering the face shape orientations
Making the panel rating a level 4 or 5
Triggering the rock burst or pre-fracturing the hazardous area

Alarm: Here a rock burst would be anticipated within days or weeks. Preventative action in this case is needed urgently and rapidly and would consist of:

Making or checking that the Panel Rating is a 4 or 5
Triggering the event
Reducing the mining rate
Moving the workforce out of the area for a some period.

Scram: This is the final strategy and requires considerable more research before field testing. In the final phase, the very sensitive seismic system would try to determinate the nucleation (start) of imminent rock-mass instability. The time period before the event would be seconds. An alarm or siren would sound and the following urgent actions taken:

Workers scramble from the face to designated safe areas
All hoisting operations stop

The Current Status

For an "alert" (seismic warning) to be successful, all events above a local magnitude 0.0 (zero) must be located by a minimum of five tree component geophone stations. This requires a very sensitive seismic monitoring system. At present, no "alert" or "alarms" are given. Until recently, only seismic "warnings" were given. This could still be wrongly construed to indicate some type of prediction in terms of rock-burst potential, that is, the time, location, and magnitude of an impending seismic event. These parameters remain impossible to predict or determine. In addition, the difference between success and failure in identifying "instability" can also depend on the skill and experience of the person conducting the interpretation.

The instability concept is derived and implemented by continuously monitoring relative stress and strain changes in the rock mass within a predetermined volume of rock. The energy index indicates the rock stress and is calculated by comparing a specific measured value against the average value for a given moment. Values of over one indicate above average stress and conversely, values below one indicate a below average stress. The strain in the rock mass is indicated by the slope (relative and not absolute) of the cumulative apparent volume, and, hence, the apparent volume indicates the deformed volume of rock during seismic event. The increase of strain and the simultaneous decrease of stress indicate instability within the rock mass. At present, the instability concept is used for only large areas (6000 + m^2), and hence the accuracy of the concept is still very approximate at best. Limitations at present are due to one, or combination of, the following:

The size and location of polygons
The seismic network configuration
The accuracy of the source parameters
The accuracy of the derived parameters
The space and time filtering of the events
The software input parameters (mostly approximations)
Interpretation is also based broadly on experience and personal opinion.

In addition, the success of preconditioning and triggering techniques has not been proven by the industry. Even with all the above limitations, AngloGold Limited-Vaal River Operations intends to continue to be a leader in the field of applied rock-burst control and continues with efforts to select appropriate techniques from industry research projects".

From the above the following sentence needs a comment: "Until recently only seismic "warnings were given". This could still be wrongly construed to indicate some type of prediction in terms of rock-burst potential, i.e. the time, location, and magnitude of an impending seismic event". First of all, "alert" with "time period of weeks" is mistaken for a "seismic warning". The latter has days or weeks attached to the event as experience indicates. Seismic warnings were never regarded as "some type of prediction", not by the Vaal Reefs seismologists, mine management, or underground personnel. There seems to be some sort of paranoia connected only with some at the rock engineering staff. By 1998, the seismologist was already a part of a rock-engineering section working directly under the supervision of a rock-engineering section head. Up to 1998, all Vaal Reefs seismologists were part of the seismic section. In this way, the responsibility for the quality and "accuracy" of warnings became the direct responsibility of a rock engineer. Their whole training and practice didn't prepare them for this type of responsibility. In my practice, I have trained a number of mine seismologists. In general, they were successful if they joined just after completing their studies, which were usually in physics. Still, the best by definition for this position is geophysicist. He was trained to analyse and interpret data, which usually appears totally unclear and chaotic to others (especially civil engineers). This also applies to the rock engineers who went through some so-called seismological training. For them, seismology was and always will be a complicated and full-of-mystery science that can only be understood by a limited number of specially gifted people. Additionally, there was a lot of confusion about what still is only a concept, what is tested, what can be implemented, what is reality, and what already is known to be fiction. This was a very serious problem that had to be at the time addressed urgently and intelligently if there would be any future for mine seismology.

6.5 Seismic Workshop and Some Memos, Date 1996–1997

A change in attitude by rock engineering staff towards the problem of seismic warnings was evident from about 1996–1997.

6.5.1 Seismic Workshop—November 1996 Recommendations

Legal advice must be obtained to investigate:

- The relationship between reliability of (seismic) interpretation and level of transparency
- To define consequences of the proposed procedures (to be followed in event of a seismic warning) as well as the COP

Some of the raised concerns:

- What are the consequences of not being able to implement the procedures fully?
- What is the legal liability chain?
- The high percentage of events following warnings has already resulted in personnel avoiding a working place or being reluctant to go there.
- How is transparency going to affect this right to refuse to work in dangerous place?

6.5.2 March 1997, Memo "Legal Questions on Rock Engineering" (Parts)

"According to the Health and Safety Act, potential hazards and risks that may be applicable to an individual must be communicated to such a person. Workers also have the right to refuse to work in a dangerous area".

“As discussed, it may be detrimental to the business if less educated staff is informed of the potential of a seismic event occurring in an area. Thus clarity on the positions of Rock Engineering and mining staff is required”.

“It is obvious that less informed people will feel threatened if told that a seismic event may occur in their place of work”.

“Present technology only indicates the potential for occurrence of seismic activity, and not the time, place or magnitude. Explaining this to less educated people may be extremely difficult and they may continue to rather be safe than sorry, i.e. ignore all explanations and rather refuse to work in a dangerous area”.

“At the recent Health and Safety Seminar the above aspects were touched on by Prof. Callen le Roux. His exposure to previous mining accidents and legal aspects distinguish him as probably the correct person to contact for advice on the “transparency” problem”.

6.5.3 End of March 1997, Memo “Verification of the Vaal Reefs Method of Stability Analysis” (Parts)—Addressed to Myself

“The method used on Vaal Reefs has been found to have some merit in location of areas where potential instability may exist in the rock mass. Concurrently, the Mining Health and Safety laws have become more stringent and onerous to those involved with mine design, specifically so in terms of transparency and informing anyone who may be subject to personal risk. The right to refuse to work in a dangerous place has also been specifically advertised. While being no less that noble in intent, the implications can be devastating to the mining effort if unsubstantiated risks are purported and less educated workers have to react to the risk. Considering the aforesaid, it would appear logical that risk can only be supported if the probability of the likely time, location area/volumetric extent and severity of such a risk can be stated. It seems to be appropriate now, to verify and quantify our methods in scientific, mathematical and statistical terms. This would put the reliability of the method into perspective, and the possibility of additional or alternative methods of seismic risk management may be explored.

Recommendations

It is recommended that a process be introduced whereby detection of rock mass instability through mine seismological methods is qualified, or at least be put in context, in terms of the probability of the likely time, location, area/volumetric extent and severity of such risk”.

6.5.4 August 1997, Memo "Rock Engineering Strategies Related to the Relevant Code of Practice" (Parts)

"The present method of seismic stability analysis was discussed in terms of the unknowns and limitations. It was stated that if a "warning" were issued it would imply that we have information about the health and safety of mine workers and that the information should then be shared with all of them. They can then quite logically and according to the Safety and Health Act, refuse to work in a dangerous working place. They are not informed/warned at present—the decisions about workers safety are taken at Shift Boss level or higher. It was recommended that the information be used in the panel rating system and for mine planning, but not according to the present "warning" procedure which incorrectly implies imminent failure and "scram" conditions according to the "alert, alarm and scram" concept. Public statements by the Company and Corporation need to reflect these limitations rather than the incorrect impression that prediction is possible"

Comments from the floor:

- The present quality of information cannot be shared with workers.
- How much of the information is relevant to the workers?
- Chief and principal inspectors should know and condone our strategy within the present limitations.
- Terminology must change from "warning" to something less indicative of "scram" conditions".

6.5.5 October 1998, Memo: "Panel Ratings, Follow-up Procedure and Seismic Warning"

This memo was addressed to all Section Heads, Rock Engineering and Seismic staff and sent to all Mine Managers (Parts).

"The seismic warning system has been a problem from various points of view since its inception. Internally, in Rock Engineering, the problems and limitations have been debated and argued towards practicability. Initially at the Business Unit Coordinating Committee meetings (9 June and July 1997), Management felt that instability should be declared if any indication existed, even if it could not be defined properly. Since then the practicalities of taking action on seismic warnings have been found to be onerous. The problem has now been raised at the highest management level. It was stated that warnings should, for example, be declared per raise line if instability is detected. This would facilitate action in a more defined geographical area. Seismic warning procedures and methodology needs immediate review. The message must get to the appropriate levels in a consistent manner. The review must facilitate a backup system so that in the absence of certain staff it does not lead to a breakdown in communication. If sufficient data does not exist to allow stability analysis on a reasonably practicably actionable geographical area, then instability should not be declared. Furthermore, risk assessment implies the hazard is identified and then the likelihood of occurrence as well as likely consequences is assessed. This also implies a measure of potential damage is known. Potential damage indicators should be identified (probably a type of magnitude). That criteria should also be satisfied before warnings are issued, i.e. possibly the likelihood of an event of greater than say magnitude 2.5 is expected, within a reasonable polygon say raise line, with a reasonable time period of ±3 days".

Actions

"Section Heads are to establish an effective seismic warning procedure that will be based on direct personal communication. The person responsible for declaring a seismic warning must communicate in person to the relevant Rock Engineering Officer (REO) and Section Manager (SM). The REO or SM or person issuing the warning, in that order will in person communicate the warning to the relevant Mine Overseer and/or Section Manager. The person affecting a warning would repeat the warning daily if required, i.e. a warning will stand only for one day.

The Section Head Seismology (that is I) will establish the criteria and methodology for effecting a stability analysis in practicable, actionable terms as described above. The methodology of stability assessment must be reasonably quantified and repeatable. The damage criteria must be set. Polygon size must be related to practicable mining pro-activity. The time prediction must indicate the urgency of action. It these cannot be made practicable so that a proper risk assessment of the seismic hazard is obtained then the endeavour to achieve such a methodology and criteria will be declared a research project by the Section Head Seismology. In regard a specific report is requested by the end of November 1998. This report is for all parties concerned".

My comment: At this stage, it becomes clear (at least to me) that the Vaal Reefs' seismic warnings were driven only by the mine management, while the rock engineers were just following their lead. Klerksdorp Regional Seismic Network from its beginning was running under the KMMA supervision. These high-ranking managers were interested in their seismic system and from the very beginning of its existence were involved. This involvement was not limited only to finance matters. They were interested in the progress of understanding the mining-induced seismicity and its application in practice. When I arrived, there was already in place among the decision-making mine management a custom to apply in practice new developments.

For all practical reasons, the just quoted memo is a direct request to remove the seismic warnings from practical application, out of mines, and out of the responsibility of the rock engineer. This was written by a rock engineer who was familiar with the method, how it works, what the limitations are, and why those limitations are in place. In this way, the warning system, from approval in early 1995, became by the end of 1998 a thread. It seems that the main problem became the legal responsibility and the need to communicate the hazard to the miners. Those are the two issues connected directly with the Safety and Health Act. The root of the problem was: "What would a reasonable manager do?" It seems that this, at least for a number of people, can be open to a very wide scale of interpretations, of which at least a number will put them on a collision course with the law. In this way, the system of seismic warnings from a technical problem became a psychological one. From being used to improve the safety of people working underground, it became something that now could ruin the safety of an engineer who is responsible for its usage. Making decisions of practical consequences is one of the basic responsibilities of every manager and engineer working in any industry. It is an everyday function as is the assumption of responsibility for the consequences. The memo required from “me establish the criteria and methodology for effecting a stability analysis in practicable, actionable terms”. The Shorter Oxford English Dictionary gives the following meanings of “practical”:

- Pertaining, or relating to practice; exhibited in practice of action (opposite to speculative, theoretical, or ideal)
- Applicable in practice; practically useful
- Engaged in practice
- Inclined to action; also having ability for action. And for “reason” (among others)
- A statement of some fact employed as an argument or justifies or condemns some act, prove or disprove some assertion, idea, or belief
- A fact or circumstance forming, or alleged as forming a ground or motive leading or sufficient to lead a person to adopt or reject some course of action or procedure, belief etc.
- That intellectual power or faculty which is ordinarily employed in adapting thought or actions to some end: the guiding principle of the human mind in the process of thinking.

It might be true that the phrase “practical reason” can sometimes have slightly different interpretations, but when narrowed to an engineering field will mean—considering the available facts and then practicalities of available actions and then making a decision and following it. Normally it is expected that not all decisions (especially in retrospection) have to be right, but they must have behind them some logic, which is defendable at any future time. Here the main problem is taking the responsibility in a situation when human life might be in danger. This might be an interesting psychological problem, but each level manager must be able to make decisions, as this is his main responsibility.

6.6 “A Guide to Routine Seismic Monitoring in Mines” (1999)

A guide as to how go about seismic monitoring in a mine as a routine practice was made accessible to the industry by the end of 1999 (Mendecki et al. 1999). According to the Oxford English Dictionary, a “guide “is the one who leads or shows the way". The first comment I received about this guide, even before I had read it, was "that the industry allowed to give the task of preparing such a document to the same people who research, produce and sell seismic equipment and software" With some changes, this guide is based on the book "Seismic Monitoring in Mines" (Mendecki 1997). This book as is stated in it acknowledgements is based on project GAP017 "Seismology for rockburst prevention, control and prediction" and project GAP 211 "Nonlinear seismology". In the preface to this book, the editor lists three objectives for seismic monitoring in mines, namely:

- To verify the parameters and assumptions of mine design while mining
- To predict larger instabilities
- To back-analyse, so that we learn from history

In the guide, there are five objectives:

- Location of potential rock bursts
- Prevention
- Control
- Warnings
- Back-analysis

The guide's prevention objective is defined as "validation of the assumptions and parameters of the design process and to enable its continuity while mining". This means that it is the same as the first objective listed in the preface. The control and warning objectives of the guide would then fall under the objective of predicting large instabilities mentioned in the book's preface. The back-analysis objective remains the same in both cases. The guide adds an additional objective for seismic monitoring, i.e. location of potential rock bursts. This was and still is the first objective of seismic monitoring, looking back into the past and at present practices. The possibility of locating future seismic events was, and still is, the main source of information about the response of the rock mass to mining. As in the past, it still can be used for a number of purposes, apart from the obvious one, that is, rapid and accurate event locations for rescue and opening up operations. The other purposes, among others, are:

- Identification of seismically hazardous geological structures
- Identification of seismically hazardous mining situations
- Establishment of criteria likely to result in seismically hazardous situations
- Relationship between blasting and seismicity
- Delineating dykes and faults ahead of mining excavations.

Locating seismic events resulted in development and implementation of a number of mining strategies used even today in the vicinity of an active dyke or a fault. Some of the applied preventative measures are listed in the guide under the prevention objective—those are corrections to the designed layout, sequence of mining, or support strategy. Furthermore, the guide returns to the concept of alert, alarm, and scram using, while this time different terminology, i.e. prevention, control, and warning. This is similar to military warning levels:

- Long-term, where the hostile situation can be still prevented
- Medium-term, where the hostile situation can still be controlled, but with possible losses
- Short-term, alarm, or scram situation where the hostilities can no longer be avoided and, in reality, a battle situation has already commenced.

It is disputable if the mining industry can implement with success the control measures as "temporary slowdown or suspension and then resumption of mining in a given area and/or the timing and desirable location of preconditioning and triggering blasts". In spite of the numerous underground excavations, access to faults or dykes is very limited, to the degree that very often their accurate locations are unknown. Furthermore, experience indicates that the rock-mass's reaction to mining changes with time and location and is not the same, even for one block of rock. There are reasons to assume that changing the rate of mining will not improve the situation but will result in the opposite. It has already been proved that temporary suspension of mining could result in postponing the event to the time of the first blast after resumption of mining (see Sect. 4.5.5). According to practicalities, there are only three main objectives for seismic monitoring:

- Location of seismic events
- Back-analysis
- Warnings or seismic hazard monitoring

In this context, back-analysis would include the objectives as described in the guide under "back- analysis" and "prevention". Preparation of seismic data for numerical modelling and for design validation purposes is in fact a back-analysis process. Such a definition of back-analysis would also include all statistical methods for evaluating seismic hazards. Now the seismic hazard monitoring would include the ones listed in the guide as "control" and "warning". As described in the guide, "control" and "warnings" are methods for monitoring levels of seismic hazard for selected areas. Both are based on monitoring the spatial-temporal changes in the same parameters. Distinction between those two implies that there is some quantification in the method applied. This is not the case. The same guide states that "quantitative stability analysis is not yet routine practice at all mines. They are currently done on the basis of qualitative interpretation of quantitative data". This implies that there are some mines that perform as routine "quantitative stability analysis" (predictions?) and some that do not. The reason for such situation was not explained as there was no definition for "quantitative stability analysis", which implies that it is a subjective matter and is based on faith. Research done for Deepmine Programme (Spottiswoode and de Beer 1999) indicates that: "A review of current seismic prediction and hazard assessment practice and capability" doesn't mention any quantitative method then in use at any mine. At the beginning of 1997, the following four levels (see Table 6.9) of seismic warning were proposed to be

Table 6.9 Conditions to invoke warnings

Warning level	Conditions
Alert 1	Anomalous spatial seismicity pattern observed in a mining area (high stress; high strain rate, high gradient in seismic flow)
Alert 2	Time history analysis shows one or more of the following:
	A significant increase in rate of ΣVa
	A significant change in level of LOG (El)
	A significant drop in Schmidt number
	The occurrence of event(s) > 1.7 (FreeGold local magnitude)
Alert 3	Anomalous temporal seismicity patterns, with one or more of the conditions specified for Alert 2 and/or two or more of the following:
	30% increase in rate of ΣVa
	Change in log(E1) > 0.25
	Drop in Schmidt number >1 order
	NB. Unless a specific sensitivity analysis was carried out for the site of concern to indicate otherwise, the moving time window will be two days and the minimum number of events used the moving time window will be five
Alarm	Conditions as specified for a particular working place, strongly suggesting the occurrence of a significant seismic event within hours

used at FreeGold. It was then expected that with time this would evolve into a more quantitative description of seismic hazards.

The Deepmine task 5.4.1 final report of January 1999 does not mention such an attempt or its results.

Changing the guide's objectives of seismic monitoring into only three groups as described would then require further changes to its content. If it is supposed to be an industry guide, then it should make clear distinctions between what is possible in practice and what is still regarded as research. Even better, it should not even contain research topics or subjects. This would help to clear up a lot of confusion, misunderstandings, and in fact terror of using seismic methods. The last can be in a direct way connected with the guide's glossary of terms. According to McGarr (1998),"the value of "Seismic Monitoring in Mines" strongly depends on one's attitude towards the parameters listed in Chap. 10 and the virtues of monitoring them". Chapter 10 of Seismic Monitoring in Mines is titled "Quantitative seismology and rockmass stability" and its author is AJ Mendecki. This also applies to the guide. When, for the first time, I saw its glossary, the following came to my mind: "The task of science is to explain actual events, processes, or phenomena in nature, and no system of theoretical ideas, technical terms, and mathematical procedures qualifies as scientific unless it comes to grip with those empirical facts at some point and in some way, and then makes them more intelligible" (Toulmin 1953). This glossary evolved into a book by Mendecki (2015) titled "Mine Seismology Reference Book". According to the author: "The Mine Seismology Reference Book grew from the paper "Mine Seismology: Glossary of Selected Terms", which was published in 2013 in the Proceedings of the 8th International

Symposium on Rockbursts and Seismicity in Mines. The idea behind the Glossary was to serve both as quick reference material and as a primer on selected terms used in mine seismology. As the scope of the Glossary broadened and volume increased, the character of the book changed to a reference book. This reference book also draws on Seismic Monitoring in Mines (Mendecki 1997) and on A Guide to Routine Seismic Monitoring in Mines (Mendecki et al. 1999)."

6.7 Summary and Conclusions

By 1997, the seismic-warning system possessed a developed methodology that made it a reliable and practical tool for managing seismicity. The seismic-warning system could not and will never be used to prevent seismic events taking place. It can only be used to raise the level of awareness of seismic hazards, and this can only result in safety improvement. Seismic warning was limited to indicating an area that might experience a seismic event and it was not time-specific, and it could not indicate the size of the future event. A seismic-warning system was in fact a method that enabled continuous seismic-hazard monitoring in a specific area. There were several limitations to the method, the most important being that it is based only on one parameter, namely, the energy index. To date, there is not a single parameter independent of seismic energy and moment that could confirm the information that is derived from the stress index. This unfortunately is the reality. One bit of information can sometimes help in solving one unknown but only the simplest one. Estimating the location of a future location of a seismic event is the easiest part of predicting because it is usually supported by mining and geological information. The size and the timing of the seismic event remain unknown. This is not surprising, as it is difficult to expect that a single bit of information could be used to solve three problems that are independent of each other, that is, location, time, and size. The logic is that, if the energy index can indicate location, then there should be a second index not based on seismic energy and moment (let's assume, for example, that this could be the seismic-activity-rate index) that would indicate the time of the event. In order to determine the event size there should be a third parameter (index) independent of seismic moment and energy as well as not connected with the seismic-activity rate. For example, it could be a seismicity-migration-pattern index. Unfortunately, these last two indexes do not exist.

Deterministic prediction of mining-induced seismic events is not possible for completely practical reasons. The main argument is the nature of the input data itself. Seismic data consists of estimates, not measurements. This was clear from the beginning of the experiment with the seismic-warning system. This is was what I explained to the mine management when I applied for the capital to build the experimental seismic network on No. 5 Shaft Vaal Reefs. Soon after completing the seismic network, seismic warnings became reality and were accepted as something that improved underground safety. No one expected that it would be possible to evacuate the miners before a seismic event and then go in and continue with the mining business. It is a fact that, in some warning cases, mining was stopped, but only because there was no second escape route in place or it was blocked and required cleaning. It seems that the decision-making mine management accepted the warning system for what it was and thought this proverb right “A wise man will receive warning, but a fool will sooner be smitten in the face” (Coverdale, Proverbs 10:8). Because of the KMMA Regional Seismic Network long history, management was used to the input from mine seismology into mining activities. For the other mines, seismology was something totally new that came from outside and, from the start, was full of mystery and secrecy. Seismology because of its language and phrases became a “black box”. Reality or concepts or just wishful thinking merged into one, especially when coming from the managers sitting right at the top of the company. Then there was the time of the great change. The Vaal Reefs Exploration and Mining Company, as everyone knew it beginning in 1944, ceased to exist as of 1998. Each shaft turned into a separate company, and some of the shafts changed hands to different and new companies. Each shaft took over its seismic network, and what was the Klerksdorp Regional Seismic Network suddenly was no longer needed. As none of the new mines had experience and know-how in mine seismology, the way out was to outsource the function to a contractor. In this way, at least in South Africa, mine seismology became a domain of only one company. Now, the rock-engineering fraternity was instructed in mine seismology from external sources. This is the way they found out that routine in seismology is alert, alarm, and scram. It was no longer a concept or idea: it was something that they must live with. The seismic warnings were no longer in place as there was no one at the shafts to carry them out. That is when and why the rock engineers started to resist the change. For obvious reasons, they could not be totally against the routine of alert, alarm, and scram, but they were able to find some issues that required attention or more research before implementing them. In this way, an initiative that provided evidence that it resulted in underground-safety improvement was abandoned. I suppose that today, that is, by mid-2017, seismic warnings are no longer used. One of the reasons for this is that there are no more mine seismologists working directly in the mines. Nowadays, mine seismology is a remote business performed away from the mines. In this way, mine seismology has started to exist on its own. It is no longer supported by other data, and it has become separated from the actual mining. As long as this situation exists, mine seismology as a science will continue to regress.

Unfortunately even if I wanted to add some “tiny” happy ending to this book there will not one. In June 2007 I was in Klerksdorp and by chance I have got hold of the local paper “Klerksdorp Record (2017)”. On the front page there was a picture of two mine shafts with a heading “Tragedy strikes mine” and further on “Four miners were killed after a seismic event on Saturday 22 July at Tau Lekoa Gold Mine near Orkney” . In the past Tau Lekoa Gold Mine was Vaal Reefs No 10 Shaft. This shaft was not covered by the KMMA Regional Seismic Network. According to Dunn (2007) Tau Lekoa seismic network of six stations was installed at the end of 2001. It was found out that the recorded seismicity correlated well with production and geology. From the end of 2001 to the end of 2002 this network recorded 263 seismic events of local magnitude above 1.0 of which 11 events were above magnitude 2.0. For this time period the largest event recorded was of local magnitude 2.8. This tragedy indicates that nearly thirty years of persistent research performed practically by one and the same organization into mine induced seismicity (seismic source mechanism, prediction, prevention and control) did not result in much of practical progress in reducing the miner's exposure to the seismic risk.

References

Adams DJ, van der Heever P (2001) An overview of seismic research co-ordinated by SIMRAC since its inception. In: van Aswegen G, Durrhein RJ, Ortlepp (eds) Rockbursts and seismicity in mines RaSim5. South African Institute of Mining and Metallurgy, Johannesburg, pp 205–212

de Beer W (2000) SIMRAC Project GAP409 Seismology for rockburst prediction. SIMRAC website: http://www.simrac.co.za

Dunn MJ (2007) Design of stable inter-pillar spans at Tau Lekoa Mine. A research report submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering, Perth

Durrhein RJ (2010) Mitigating the risk of rockbursts in the deep hard rock mines of South Africa: 100 years of research. In: Brune J (ed) Extracting the science: a century of mining research. Society for Mining, Metallurgy, and Exploration, Inc. ISBN 978-0-87335-322-9, pp 156–171

Dzafarov AD (1998) SIMRAC Project GAP211 Non-linear seismology. SIMRAC website: http://www.simrac.co.za

Geller RJ (1997) Earthquake prediction: a critical review. Special Section- Assessment of Schemes for Earthquake Prediction. Geophys J Int 131:425–450

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

Hodgson DL (1999) SARES 99 keynote address: present and future trends of the gold industry and the role of rock engineers. In: Hagan TO (ed) SARES 99 2nd Southern African rock engineering symposium, Johannesburg, South Africa

Kagan YY (1997) Are earthquakes predictable (Special Section—Assessment of Schemes for Earthquake Prediction). Geophys J Int 131:505–525

Klerksdorp Record (2017) vol 132, Week 30

McGarr A (1998) Book review of Seismic monitoring in mines. In: Mendecki A (ed) Rev Pure Appl Geophys 152:179–181

Mendecki AJ (2015) Mine seismology reference book publisher: institute of mine seismology. ISBN: ISBN978-0-9942943-0-2. http://www.researchgate.net/publication/280312830_Mine_Seismology_Reference_Book

Mendecki AJ (1995) SIMRAC Project GAP 017 Seismology for rockburst prevention, control and prediction. SIMRAC website: http://www.simrac.co.za

Mendecki AJ, van Aswegen G, Mountford P (1999) A guide to routine seismic monitoring in mines. In: Jager AJ and Ryder JA (eds) A handbook on rock engineering practice for tabular hard rock mines. Safety in Mines Research Advisory Committee, Johannesburg. Creda Communications, Cape Town, pp 287–309

Mendecki AJ (ed) (1997) Seismic monitoring in mines. Chapman and Hall, London

Nicolau NF (1996) Interaction between the seismic alert/alarm concept and mining practice at Vaal Reefs. In: Papers and Discussions 1996–1997, Association of Mine Managers of South Africa

Ortlepp WD (1997) SIMRAC Project GAP 346 Audit/review of project GAP 017. SIMRAC website: http://www.simrac.co.za

Spottiswoode SM (1997) SIMRAC Project GAP 345 Audit of SIMRAC project GAP 017. SIMRAC website: http://www.simrac.co.za

Spottiswoode SM (2000) Mine seismicity: prediction or forecasting. J S Afr Inst Min Metall 110:11–20

Spottiswoode SM, de Beer W (1999) A review of current seismic prediction and hazard assessment practice and capacity. Deepmine final report task 5.4.1. Review of current seismic prediction and hazard assessment practice and Capability Johannesburg. Deepmine Consortium

Toulmin SE (1953) An introduction to philosophy of science. https://archive.org/details/philosophyofscie032167mbp

van der Heever P (2002) Practices and initiatives to transfer Simrac developed technologies to its stakeholders and other parties. J S Afr Inst Min Metall 2002:283–288

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